Final Report

Addendum
Natural Pressure-Driven Passive Bioventing

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Abbreviations and Acronyms

AFB	Air Force Base
amsl	above mean sea level
AST	aboveground storage tank
BFS	bulk fuel storage
bgs	below ground surface
BTEX	benzene, toluene, ethylbenzene, and xylenes
cfm	cubic feet per minute
DoD	Department of Defense
ESOH	Environmental Safety and Occupational Health
ESTCP	Environmental Security Technology Certification Program
FSMR	Fort Stewart Military Reservation
GEPD	Georgia Environmental Protection Division
I.D.	inside diameter
IRP	Installation Restoration Program
MCAGCC	Marine Corps Air Ground Combat Center
MW	monitoring well
NFESC	Naval Facilities Engineering Service Center
O&M	operations and maintenance
O.D.	outside diameter
POL	petroleum, oils, and lubricants
ppm	parts per million
PVC	polyvinyl chloride
RCRA	Resource Conservation Recovery Act
RFA	RCRA Facility Assessment
RFI	RCRA Facility Investigation
SCAPS	Site Characterization and Analysis Penetrometer System

SWMU	solid waste management unit
SVOC	semivolatile organic compound
TDP	Technical Demonstration Plan
TPH	total petroleum hydrocarbons
U.S. EPA	United States Environmental Protection Agency
UST	underground storage tank
VOC	volatile organic compound
WAAF	Wright Army Air Field
WR-ALC	Warner Robins Air Logistics Center

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Preface

This addendum to the final report *Natural Pressure-Driven Passive Bioventing* (ESTCP, 2000) describes the additional site characterization field activities conducted at Fort Stewart, GA, and Robins Air Force Base (AFB), GA. Based on data collected during the site-screening process at ten (10) eastern U.S. sites, as well as lithologic features described in existing reports for the sites (NFESC, 2001a), these two sites were selected to undergo further characterization in order to determine the most suitable site for a long-term passive bioventing demonstration.

Based on the results from the additional site characterization work at Fort Stewart and Robins AFB, which are described in detail in this final report addendum, it was determined that passive bioventing would not be a suitable remedial alternative for either site. Consequently, it was concluded that passive bioventing has limited application at eastern U.S. sites, and it was decided, in consultation with ESTCP, not to proceed with the long-term demonstration portion of this project.

1. Introduction

1.1 Background Information

Passive bioventing is a technology that provides an option for remediating hydrocarbon-contaminated vadose-zone soils. This technology is applicable to organic contaminants (such as petroleum hydrocarbon compounds) that are biodegradable under aerobic conditions. Natural

pressure-driven bioventing is a variation of conventional (i.e., active) bioventing. Active bioventing is a proven, cost-effective technology that has been applied at numerous Department of Defense (DoD) installations (Leeson and Hinchee, 1997).

Whereas active bioventing requires a blower to inject ambient air into the contaminated soil, passive bioventing transfers ambient air into and out of the vadose zone through barometric pressure fluctuations and the resulting pressure differential between the atmosphere and subsurface soil gas. In both cases, oxygen is provided to the indigenous microorganisms, which promotes mineralization of the hydrocarbon contaminants.

The potential benefits of passive bioventing over active bioventing are simplicity of design and its use at remote sites where electrical power either is unavailable or is cost-prohibitive to install. When compared to conventional bioventing, passive systems would be expected to have reduced operations and maintenance (O&M) requirements and costs, potentially less facility disruption, and increased reliability through simplicity.

This final report addendum provides a summary of the activities associated with characterizing/ identifying a site for a long-term demonstration of natural pressure-driven passive bioventing. Of interest was locating a site that had measurable hydrocarbon contamination, depleted soil-gas oxygen levels (<3%), and a shallow vadose zone (NFESC, 2001b). Additionally, the lithological features at such a site would permit the lateral movement of air in the formation, while having confining surface characteristics.

Sites that were previously identified as potentially meeting these criteria were Fort Stewart and Robins AFB (NFESC, 2001a). These sites underwent characterization to determine if they displayed the criteria that permitted their use during a long-term demonstration of natural pressure-driven bioremediation technology.

1.2 Official DoD Requirement Statements

This technology demonstration addressed the following DoD requirements:

1. Navy requirement number 1.I.1.m – Improved Remediation of Soils Contaminated with Non-Chlorinated Hydrocarbons.

2. Air Force requirement Environmental Safety and Occupational Health (ESOH) Need #243 – Site Remediation, Hazardous Waste Treatment Technologies for Installation Restoration Program (IRP) Site Remediation of Hydrocarbon Compounds in Soil.

These requirements were addressed through the investigation of passive bioventing as a potentially cost-effective alternative to conventional bioventing. These investigations were conducted at sites with petroleum-hydrocarbon contamination in soils. The real-time monitoring of passive air movement into the soil was used as the primary indicator of potential treatment effectiveness for the bioremediation of the site contaminants.

1.3 Objectives of the Demonstration

The objective of this demonstration was to determine the applicability of passive bioventing to site conditions other than those previously studied. Of primary interest was the application of passive bioventing at sites with shallow aquifers, spatially limited vadose zones, and in environments having higher and more uniform precipitation than previously evaluated sites, which were mainly in the southwestern United States.

The specific objectives of the reported site characterizations were:

1. Evaluate the passive approach under geologic conditions not previously investigated;

2. Measure the airflow rates associated with variations in barometric pressure;

3. Gather data to support recommending a long-term demonstration of passive bioventing at a shallow vadose zone site in the eastern United States (NFESC, 2000).

The scope of this demonstration required to satisfy the above objectives was:

1. Conduct a site survey at two locations with characteristics deemed conducive to passive bioventing, but which had not been studied previously (i.e., lithologically stratified permeable, but high moisture content soils with shallow groundwater);

2. Collect data to aid in the evaluation of how site variables (e.g., barometric pressure, soil moisture, temperature, soil-gas oxygen, hydrocarbon, and carbon dioxide concentrations, stratigraphy, and well configuration and depth) affect airflow rates and oxygen concentrations in the subsurface;

3. Collect barometric pressure-driven airflow data into the soil formation.

The performance objectives that needed to be met in order to recommend proceeding with a long-term demonstration were:

1. Achieve airflow rates sufficient to meet biological demand (i.e., peak airflow rates on the order of 1 ft^3/minute per vent well and total airflow rates on the order of 1,200 ft^3/day per vent well) (NFESC, 2001b);

2. Achieve an adequate radius of influence (on the order of 10 ft per vent well) to be economically viable (i.e., ability to achieve an economical radius of influence, without an excessive number of vent wells required, when compared to a conventional bioventing approach).

This technical report and accompanying data indicate that the site characterization objectives have been met and makes a recommendation on whether or not a long-term demonstration should be performed at the study sites (i.e., Fort Stewart and Robins AFB).

1.4 Regulatory Issues

Regulatory issues that apply to contaminated soil cleanup generally are driven by federal, state, or local standards. Cleanup concentrations typically are dictated by human health, risk-based remediation goals.

As of October 1994, regulatory acceptance of bioventing as an applicable remedial technology had been obtained in all 10 U.S. EPA regions and in 30 states (U.S. EPA, 1999). If a passive approach is shown to be technically equivalent to the active method, then the potential exists of having it equally accepted as a remedial technology.

The effectiveness of passive bioventing could be demonstrated to regulatory agencies by performing the same monitoring as for active bioventing. This monitoring would include periodic in situ respiration tests and confirmatory soil sampling. By employing an one-way passive valve that allows only air movement into the soil (see Section 2.1.3), the exhalation of soil-gas vapors to the atmosphere would be avoided and would negate the need for air emission permitting.

State and local regulatory issues associated with work plans, digging permits, well installation permitting, and the disposal of any waste generated during installation activities would remain applicable for passive bioventing.

1.5 Previous Testing of the Technology

Passive bioventing has been demonstrated prior to this ESTCP project at the following two DoD sites and one Department of Energy (DOE) site in the continental United States.

- Marine Corps Air Ground Combat Center (MCAGCC) in Twentynine Palms, CA: barometric pressure changes resulted in airflow rates of up to 7 cubic feet per minute (cfm) into vadose zone wells (Foor et al., 1995; and Zimmerman et al., 1997). Depth to groundwater at this test site was approximately 200 ft below ground surface (bgs) and the lithology was primarily medium- to coarse-grained sands. A 9-ft radius of influence from the injection well was confirmed by elevated oxygen concentrations in the soil gas. Potential radii of influence of up to 20 ft were calculated, based on soil-gas pressure measurements.

- Hill AFB, UT: passive airflow rates of up to 5 cfm were measured in a 100-ft vadose zone (Battelle, 1995).

- Savannah River site, SC: passive airflow rates of up to 6 cfm were recorded where the depth to groundwater was 120 ft bgs (Rossabi et al., 1993 and 1998).

These sites all possessed the similar characteristics of deep groundwater, extensive vadose zones, and relatively permeable low moisture-content soils.

2. Technology Description

2.1 Description

2.1.1 Introduction. Bioventing is the process of aerating water-unsaturated (vadose zone) soils to stimulate in situ biological activity and promote bioremediation (Leeson and Hinchee, 1997). The technology generally utilizes the oxygen associated with ambient air to transform anaerobic conditions in hydrocarbon-contaminated soils to aerobic conditions. Oxygen in the soil-gas allows the indigenous aerobic microorganisms to utilize the hydrocarbons present in the soil as a "food source". This mineralization process results in the reduction of hydrocarbon contaminants in the soil with carbon dioxide, water, and microbial biomass being generated as byproducts.

Bioventing is a relatively "low tech" approach to soil remediation, which makes it an appealing alternative to the potentially expensive dig-and-haul option. To implement conventional (i.e., active) bioventing at a site, a site survey is performed, vent wells and soil-gas monitoring points are installed, and ambient air is pumped into the vent wells using one or a series of blowers (Figure 1). The air injection process delivers the required oxygen to the soil so that bioremediation can occur. Flowrates are adjusted to optimize soil aeration, while minimizing volatilization, soil dessication, and the possible vapor transfer of hydrocarbons from the unsaturated soil into the atmosphere or groundwater. Bioventing performance is monitored by drawing soil-gas samples from the monitoring points. Elevated concentrations of oxygen in the soil gas indicate that the soil is being aerated at a rate that exceeds biological demand. By performing in situ respiration tests, which determine oxygen utilization rates and subsequently the hydrocarbon degradation rates, it is possible to determine how rapidly the hydrocarbon contaminants are being degraded and when it is appropriate to perform final soil sampling.

2.1.2 Passive Bioventing. The primary difference between active and passive bioventing is the mechanism associated with delivering oxygen to the vadose-zone soil gas. Whereas active bioventing relies upon the mechanical pumping of ambient air into the vadose zone with a blower, passive bioventing utilizes the differential pressure between the atmosphere and the subsoil to move air into the soil formation. Changes in barometric pressure can cause wells that terminate in the vadose zone to "breathe" in and out (Foor et al., 1995; and Zimmerman et al., 1997). If the relative pressure in the soil gas is low and the barometric pressure is higher, then air moves into the soil formation. If the reverse is the case, then soil gas exhales from the soil formation into the atmosphere.

The mechanisms that drive passive bioventing are barometric pressure changes, depth of the vadose zone, soil-gas permeability, and soil porosity (Zimmerman et al., 1997). Because diurnal temperature changes impact barometric pressure, air temperature fluctuations can sometimes have a major effect on the movement of air into and out of the soil formation. Also, soil

moisture can affect the permeability of air flow through the subsurface soils (e.g., water-saturated gravel provides for no air flow).

2.1.3 Passive Bioventing Design Considerations. The major difference between active and passive bioventing is that the former involves the installation of vent wells with blowers, whereas the latter involves the use of passive valves. All other aspects of conventional bioventing (monitoring point installation, in situ soil-gas monitoring, and final soil sampling [Leeson and Hinchee, 1997]) are employed by both technologies.

Whereas active bioventing provides a constant flow of air into the soil formation, passive bioventing typically provides "slugs" of air when the differential pressure between the atmosphere and the vadose zone permits barometric pumping. In order to optimize the use of all of the oxygen that enters the soil formation, it is necessary to restrict any air movement out of the vadose zone because the rate of oxygen utilization by soil microorganisms is less than the desired rate of oxygen injection during active air flow into the vent well. The control of the air movement process is possible through the use of a one-way passive airflow valve (Figure 2). The passive valve allows air to move into the vent well but closes the well when air tries to escape. This not only optimizes the use of the available oxygen for bioremediation but also restricts the movement of any volatile organic compounds (VOCs) from the soil to the atmosphere.

2.2 Strengths, Advantages, and Weaknesses of Bioventing

2.2.1 Strengths, Advantages, and Weaknesses of Active Bioventing. The primary advantage of active bioventing over other soil-remediation technologies is technological simplicity and cost-effectiveness. This technology can be applied to a wide range of organic contaminants and it does not require major disruption of a site, as would be the case with dig-and-haul.

The major weakness is that it is limited to the vadose zone and compounds that are aerobically biodegradable. It is possible to treat the saturated zone by carefully air sparging the volatile contaminant fraction and transporting it into the vadose zone, but this increases engineering efforts and costs. Additionally, active bioventing is useful for preventing the continued migration of contaminants, but these systems rarely achieve typical cleanup goals (Leeson and Hinchee, 1997).

The same weaknesses apply to passive bioventing.

2.2.2 Advantages of Passive Bioventing over Active Bioventing. The primary advantages of passive bioventing are the elimination of the blower and electrical power requirements. An additional advantage is that if a currently active bioventing site is deemed suitable for passive bioventing, then it may be possible to utilize existing vent wells, install passive-bioventing valves, and convert from active to passive mode as a polishing step in the remediation process.

2.2.3 Weaknesses of Passive Bioventing when Compared to Active Bioventing. Active bioventing is more appropriate than passive bioventing at sites where there are low barometric

pressure changes, where the soils display relatively low air permeability, and where there are very shallow vadose zones. Other weaknesses associated with a passive (i.e., nonblower) bioventing system include low and intermittent airflow rates. Even with acceptable peak flowrates, on the order of 1 cubic foot per minute (cfm), these rates would not be expected to be maintained for a greater portion of a 24-hour day. Therefore, the intermittent delivery of air to shallow vadose zones may not be able to meet the oxygen demand, which would extend the length of time required to accomplish remediation goals.

2.3 Factors Influencing Cost and Performance

Airflow rates and the resulting radius of influence are critical in determining the cost and performance of both active and passive bioventing systems. As the radius of influence decreases due to low flowrates, the number of vent wells increases. The point at which passive bioventing vent-well installation costs exceed blower and electrical installation and operating costs, is the point at which passive bioventing is no longer economically feasible.

The expected radius of influence and airflow rates are primarily a function of the following site characteristics:

- Magnitude of barometric pressure fluctuations
- Frequency of barometric pressure fluctuations
- Air permeability in the soil (functions of soil type, soil porosity, and soil moisture)
- Oxygen-utilization rate of the microorganisms.

As with any bioremediation process, soil temperature, naturally occurring organic carbon, types of contaminants, soil pH, and nutrient availability all can have an effect on how rapidly and efficiently oxygen is utilized to mineralize hydrocarbon contaminants (Leeson and Hinchee, 1997). The rate of biological activity has a direct bearing on how quickly remediation goals are achieved and therefore how long bioventing must be performed and financially supported.

An additional cost consideration associated with long-term operations is extended monitoring activities. It may be necessary to dramatically reduce any in situ respiration testing (annually instead of quarterly); otherwise, the cost associated with the field activities could rapidly negate the benefits of bypassing blower operation and power requirements.

3. Site/Facility Description

This section provides site/facility descriptions for Fort Stewart and Robins AFB, where additional site characterization activities were performed.

3.1 Fort Stewart Site/Facility History

Fort Stewart Military Reservation (FSMR) is located approximately 40 miles west-southwest of Savannah, GA (Figure 3). The installation was established in 1940 as an antiaircraft artillery

training center. FSMR was deactivated in 1945 and subsequently reactivated in 1950 to train artillery units for the Korean Conflict. In 1974, Fort Stewart became a training and maneuver area, providing tank, field artillery, helicopter gunnery, and small arms training for regular Army and National Guard units. The 3rd Infantry Division was permanently stationed at Fort Stewart in 1975.

The Wright Army Air Field (WAAF) Bulk Fuel System (BFS) is located approximately 1.2 miles east of the Fort Stewart garrison area on the southern boundary of the Base (Figure 4). The BFS began operations in 1988 and provided fuel storage for airfield operations in support of the 3rd Infantry Division. The WAAF BFS currently is not active and trucks are used for refueling activities. Two 25,000-gallon aboveground storage tanks (AST) filled with JP-8 jet fuel, an oil/water separator, a hot refuel point, and the associated pipelines were present at the site, but since have been removed. Prior to the present configuration, two 10,000-gallon underground storage tanks (USTs) were used for fuel storage. These tanks were abandoned in-place in 1988 upon completion of the AST facility. The USTs were drained, cleaned, and filled with sand. Clean fill was placed on top of the USTs (from approximately 10 ft bgs to the existing grade). The overhead dispensers associated with the USTs were removed. The concrete islands that supported the dispensers still remain. In 1996, concrete was installed under the aboveground piping associated with the ASTs. During the excavation for placement of the concrete pad, elevated petroleum concentrations were encountered, resulting in a shutdown of the site. Both the soil below the aboveground piping and the fill used to cover the USTs were removed from the site. The excavations then were backfilled with clean soil. The source of the soil contamination was determined to be from leaks in the aboveground piping.

The Georgia Environmental Protection Division (GEPD) issued a Resource Conservation and Recovery Act (RCRA) Permit to Fort Stewart in 1987 for the storage and treatment of hazardous waste. During RCRA Facility Assessments (RFAs) at Fort Stewart, a total of 33 solid waste management units (SWMUs) were identified. Nine of these required no action. RCRA Facility Investigations (RFIs) were performed for the remaining SWMUs. SWMU 35 was the WAAF BFS, and Phase I RFI fieldwork was performed between March and June 1996. The Final, Phase I RFI Report for SWMU 35 was submitted to GEPD in December 1996. The GEPD instructed the Fort Stewart Directorate of Public Works to conduct a Phase II RFI at SWMU 35. This was performed in 1998, and a revised Final, Phase II RFI was submitted in May 2000 (SAIC, 2000).

3.1.1 Fort Stewart Site/Facility Characteristics. The following sections provide site/facility characteristics that qualify the applicability of passive bioventing at the Fort Stewart site.

3.1.1.1 Climate. Climatological data is based on information from the Georgia State Climate Office at the University of Georgia (climate.engr.uga.edu/pubs/coastal.pdf).

Fort Stewart is located in the Georgia Coastal Plain. Coastal plain temperatures have an average high above 77ºF and an average low around 54ºF. Cities along the coast, such as nearby

Savannah, experience more moderate temperature extremes than inland areas. Savannah typically experiences approximately 70 days with temperatures in excess of 90ºF and 26 days with low temperatures of 32ºF or below.

Annual precipitation along the coastal region averages in excess of 45 inches and decreases inland to the north and west. The average number of precipitation days is 121 per calendar year. The summer months (associated with hurricane season) account for most of the annual precipitation, with the fall being the driest season. Snowfall is uncommon and typically associated with infrequent winter storms.

3.1.1.2 Geology. The FSMR occupies a low-lying, flat region on the coastal plain of Georgia. Surface elevations range from ~20 to 100 feet above mean sea level (amsl) and generally decrease from the northwest to the southeast.

The major soil types in the region of FSMR range from well-drained, nearly pure sand to poorly drained mixtures of loam, sand, and clay. Boring logs from Phase II RFI indicate clayey sand soil (Stilson Series) that typically extends from 15 to 18 ft bgs in the area of SWMU 35. The soil type has moderate permeability and a low water-bearing capacity.

The Stilson Series clayey sand soil overlies two distinct geologic deposits ranging from silty sands to clean, well-sorted sands. The silty sands are at depths ranging from 16 to 25 ft bgs and are characteristic of back-barrier, lagoon, and stream-channel deposition environments. The well-sorted sands generally are found at depths below 25 ft, are medium- to coarse-grained, and are characteristic of a littoral deposition environment. These littoral sands comprise the primary water bearing zones across SWMU 35 and appear to be highly permeable and transmissive.

Historical presentations of two transverse cross sections and a longitudinal cross section (SAIC, 2000) are provided in Figures 5, 6, and 7, respectively.

3.1.1.3 Hydrology. The hydrology in the vicinity of the FSMR is dominated by two aquifers referred to as the Principal Artesian aquifer and the surficial aquifer. These two aquifers are separated by a confining unit.

The Principal Artesian aquifer is the lower hydraulic unit and is regionally extensive from South Carolina through Georgia, Alabama, and most of Florida. This formation is approximately 800 ft thick and this groundwater is used primarily for drinking water. Its confining layer is phosphatic clays of the Hawthorn Group.

The upper hydraulic unit is the surficial aquifer, which consists of widely varying amounts of sand, silt, and clay ranging from 55 to 150 ft thick. Water usage from this aquifer is primarily for both domestic and agricultural irrigation. The top of the water table ranges from 2 to 10 ft bgs. However, occurrences of perched water table within the Stilson loamy sands are present within FSMR.

Groundwater at SWMU 35 generally flows to the southeast from the hot refuel area toward the vicinity of monitoring well MW06, MW07, and MW19 (Figure 8). Water table elevation data collected in February 1999 show a range from 33.7 to 29.81 ft amsl. Horizontal gradients range from 0.0009 ft/ft east to west to a maximum of 0.006 ft/ft from the northwest to the southeast. Based on data from paired wells (MW04/13, MW14/15, and MW16/17 in Figure 8) no appreciable vertical gradients exist above the Hawthorn Group and water level differences in paired wells varied by 0.06 ft or less. Porosity of the subsurface materials from MW14 (0.33) is within the expected range for sands, and the permeability of the soil was low (4.83E-05 cm/sec) despite the high sand fraction (90.5%) contained in the sample.

3.1.2 Nature and Extent of Contamination. Extensive investigations into the extent of contamination associated with the surface soil, subsurface soil, and groundwater have been performed at SWMU 35. VOCs, semivolatile organic compounds (SVOCs), and metals have been tested for in these matrices. This addendum discusses only the organic compounds, because they are the contaminants that usually are targeted by the bioventing process.

Remedial investigation activities have included:

- Near surface and subsurface soil sampling and analysis for VOCs and SVOCs;
- Shallow and deep groundwater sampling and analysis for VOCs, SVOCs, and total petroleum hydrocarbons (TPH).

3.1.2.1 Surface and Subsurface Soil Contamination. Low levels of VOCs and SVOCs were detected in the surface and subsurface soils at SWMU 35.

Surface soil contamination from VOCs (2-butanone, 2-hexanone, acetone, benzene, ethylbenzene, toluene, and total xylenes) was located primarily in the region around MW04; SVOCs were located primarily in surface soils in the vicinity of MW13 (see boring location SB12 on Figure 9). All of these locations are either within, adjacent to, or downgradient of the areas where previous releases are to have occurred. These include the hot refuel area, areas affected by known underground pipe leaks and spills, and the aboveground storage tank bermed areas.

Subsurface soil contamination from VOCs (1,1,2-trichloroethane, 2-butanone, 2-methylnaphthalene, acetone, benzene, chloroform, ethylbenzene, methylene chloride, styrene, toluene, and total xylenes) was detected primarily in the vicinity of MW13, and low-level SVOCs were detected at MW04 and MW13 (Figure 10).

3.1.2.2 Groundwater Contamination. The groundwater monitoring network at SWMU 35 has MW09 and MW10 located downgradient of potential contaminant areas. MW09 had detectable concentrations of benzene and total xylenes (Figure 11). No organics were detected in MW10. Wells MW02 and MW11 are located hydraulically upgradient of the source of contaminants, yet these also have detectable concentrations of benzene and total xylenes.

3.1.2.3 Estimated Area of Subsurface Organic Contamination. Based on the data from surface soil, subsurface soil, and groundwater sampling and analysis, the contaminant concentration at SWMU 35 are presented in Figure 11. It is within this area that additional site characterizations (a soil-gas survey and vent well installation) took place, and would be the area where the passive bioventing demonstration would be conducted.

3.1.2.4 Location of Site Characterization. The target area for the passive bioventing study was selected based on the previously discussed site characteristics. The primary consideration was the location of hydrocarbon-based fuel products in the soil. This was determined by examination of previous site characterization work. The extent of contamination indicated in Figures 9 and 10 were used to select areas that were considered to be favorable targets.

Next, the geological features present at the site were examined to narrow the potential locations for additional characterization. The information from the cross-sections presented in Figures 5, 6, and 7 was used to delineate subsurface features that would be favorable for passive bioventing. The sand and gravel layers were examined in relation to the location of the fuel contamination. It was determined that the area underlying (and to the immediate east of) the former dispenser island was the best potential location. A thin pebble zone in the soil, just above the water table, was the target zone for the testing. A secondary area, underlying the former ASTs, was chosen as a secondary target area.

The last step in target area selection was the presence of surface and subsurface infrastructure. The site is developed as a support area for aircraft and is mostly covered with concrete and asphalt pavement. The area below the former ASTs currently is open and covered with grass. In the vicinity of the dispenser island, refueling trucks are stored in above ground impoundments for secondary containment of spills. Much of the surface cover in this area is thick (>12 inches) runway grade reinforced concrete. Beside the truck storage area is a small gravel island that was selected as a candidate target for the study.

Four areas were ultimately chosen as candidates for further study (see Figure 12). The areas were numbered in order of the suitability for additional investigation. Area 1 is the gravel island near the former fuel dispensers. Areas 2 and 3 are in the grass and the asphalt circle adjacent to the former ASTs. Area 4 is located in the concrete driveway beside Area 1.

3.2 Robins AFB Site/Facility History

Robins AFB and the Warner Robins Air Logistics Center (WR-ALC) are located approximately 16 miles south of Macon, GA (Figure 13). The base is situated on approximately 8,722 acres of upper coastal plain, including 2,300 acres of wetlands and 1,150 acres of timberland. Construction of the facility by the former Army Air Force began in September 1941 and the airfield's industrial and contonment areas were completed by April 1943. The current designation of the industrial portion of the facility, WR-ALC, was changed to its present form in 1974 in honor of its namesake Brigadier General Augustine Warner Robins.

Currently, the WR-ALC and Robins AFB are the largest industrial facilities in the State of Georgia, employing approximately 5,000 military and 13,000 civilians. The WR-ALC is responsible for the supply of parts for maintenance, repair, and storage of vital defense aircraft.

3.2.1 Robins AFB Site/Facility Characteristics. The following sections provide site/facility characteristics that qualify the applicability of passive bioventing at UST Site 2070/2072, Robins AFB.

3.2.1.1 Climate. Climatological data are based on information from the Georgia State Climate Office at the University of Georgia (http://climate.engr.uga.edu/pubs/piedmont.pdf).

Robins AFB is located in the Georgia Piedmont region, which covers approximately one-third of the total land area of the state. The Piedmont Region lies between the coastal plan to the southeast and the Georgia Mountain Province to the northwest. Piedmont Region average high temperature is 74ºF. The summer average temperature is 89ºF and the winter average temperature is 57ºF. Nearby Macon, GA typically experiences approximately 84 days in excess of 90ºF.

Annual precipitation across the Piedmont Region averages in excess of 40 inches.

3.2.1.2 Geology. Robins AFB is located on the southern edge of the Georgia Piedmont Province immediately west of the Ocmulgee River. The soils of the Piedmont are predominately sandy loams to clay loams and are typically well suited for the production of crops.

Three subsurface soil zones have been identified at the site: a shallow sandy unit, an intermediate clay unit, and a deeper sandy unit interbedded with clay lenses (Earth Tech, 2001).

The shallow sandy unit contains cover or fill material, and the principal lithology is a fine to coarse grained, well-graded silty sand. Lenses of sandy clay are distributed throughout the unit. The top of a light gray clay layer marks the base of this shallow unit.

The intermediate clay layer begins at approximately 30 ft bgs and increases in depth to the east of the site. The clay is usually light in color, very firm and dry, contains up to 30% sand, and can locally be plastic or nonplastic. The average thickness of the clay layer is approximately 20 ft.

The passive bioventing investigation was conducted in the upper, shallow silty sand unit.

3.2.1.3 Hydrology. Shallow groundwater occurs in the upper silty sand unit and is perched above the intermediate clay unit. Generally, groundwater flow in this perched aquifer is to the south and west. This water is separated from the underlying Upper Providence Aquifer in this area by the intermediate clay unit. The confining clay unit has been reported to be bowl-shaped and confines the perched groundwater to a very localized area (Earth Tech, 2001).

Groundwater flow in the vicinity of Site 2070/2072 is in an easterly direction (Figure 14) with a depth to groundwater of approximately 8 ft bgs.

3.2.2 Nature and Extent of Contamination. The chemicals of potential concern identified in previous investigations are organics associated with JP-4 jet fuel. The source of the fuel contamination is probably the result of a fuel leak at the Lateral Control Pit 3, which occurred in February 1995 (Geophex, 1999). This would put the source upgradient of Site 2070/2072.

3.2.2.1 Surface and Subsurface Soil Contamination. Previous investigations at the site delineated benzene, toluene, ethylbenzene, and xylenes (BTEX) concentrations in the soil gas and soil (Geophex, 1999). Additionally, TPH measurements were made. At depths ranging from grade to 4 ft bgs (Figure 15), the soils in the vicinity of monitoring well EA2 had displayed soil hydrocarbon concentrations of 35 ppm with no BTEX or TPH detected in the soil. However, at a depth of 4 to 9 ft bgs, well EA2 had soil hydrocarbon concentrations that exceeded 1,000 ppm and TPH levels in the soil were 4,900 ppm (Figure 16). BTEX concentrations in the soil were 141.5 ppm.

3.2.2.2 Groundwater Contamination. A Site Characterization and Analysis Penetrometer System (SCAPS) was used to characterize Site 2070/2072 in February 1995 (Geophex, 1999). The SCAPS was employed to delineate free product/residual soil contamination at the site. In the vicinity of well EA2, groundwater and soil contamination ranged from nondetects to a 3.6-ft zone of contamination (Figure 17). Only these qualitative data were available for the site.

3.2.2.3 Estimated Area of Subsurface Organic Contamination. The area of subsurface contamination was consistent for the previous site characterization activities. The contamination appears to originate just to the west of well EA2 and be dispersed to the east and southeast (Figures 15, 16, and 17). This would be consistent with groundwater directional transport (Figure 14), which likely has contributed to the migration of the hydrocarbon contaminants.

3.2.2.4 Location of Site Characterization. By installing the vent well for the passive bioventing site characterization activities approximately 12 ft to the west of EA2 (Figure 18), the well should have been located within the zone of contamination.

4. Demonstration Approach

4.1 Performance Objectives

As discussed in Section 1.3, the performance objectives for this site characterization effort were the following:

- Achieve airflow rates sufficient to meet biological demand (i.e., peak airflow rates on the order of 1 ft^3/minute per vent well).

- Achieve total airflow rates on the order of 1,200 ft^3/day per vent well.

- Achieve a radius of influence around each vent well of ≥10 ft.

If flowrates did not approach these levels, then an excessive number of vent wells would have to be installed, which would defeat the cost-effectiveness of the passive technology.

4.2 Physical Setup and Operation

4.2.1 Site Characterization Soil Borings at Fort Stewart. The site investigation involved five individual phases: (1) the site was marked for all underground utilities, (2) a soil-gas survey was conducted to narrow the potential locations for a vent well, (3) soil cores were collected to examine the lithology, (4) a vent well was installed, and (5) a data logging system was installed to monitor the vent well.

The locations of the intrusive work were selected within Areas 1 through 4 (as described in Section 3.1.2.4) and placed carefully to avoid encountering subsurface utilities. Several water supply lines and electrical utilities were identified within the selected areas. The locations of the 14 soil-gas monitoring points from the soil-gas survey are indicated in Figure 12.

Soil-gas samples were collected using a small track-mounted drilling rig with a 1-inch diameter direct-push sampler. Samples were collected from each monitoring location at depths of 5, 10, and 15 ft. The sampler consisted of a retractable drive point with a sealed chamber with a disposable septa at the top. When the sampler was driven to a selected depth, the tip was opened by slightly retracting the drive pipe. A sample tube was connected to the tip by lowering a polyethylene tube with a weighted coupler into the pipe. A hypodermic needle in the coupler pierced the septa and allowed the soil gas in the surrounding formation to be collected. A vacuum pump was first employed to transfer the sample to a Tedlar™ bag, but it was determined that the pump pulled too much vacuum and a hand squeeze bulb was substituted for most of the readings. Measurements of O_2, CO_2, and TPH were analyzed with calibrated handheld field instruments. A GasTech GasTechtor™ was used for the O_2 and CO_2 measurements. A GasTech TraceTechtor™ and a Photovac MicroFID were used to measure the hydrocarbons present in the soil gas. Results of the soil-gas survey are shown in Table 1. The soil gas in several of the monitoring wells at the site was measured to determine the concentrations of O_2, CO_2, and TPH in the headspace of the wells; these results also are included in Table 1. In general, the low permeability of the soil at the site made collection of the soil-gas samples difficult, and several sample points, including the wells, resulted in sufficient vacuum being drawn on the wells to limit further collection of samples. Additional soil-gas samples later were collected using hand-driven soil-gas sampling rods to confirm the results obtained by the first method (Table 1). The results of the second survey indicate that the readings from the initial survey were representative of the conditions at the site.

Three soil cores were advanced based on the results of the soil-gas survey in an attempt to locate the most favorable location to install a vent well. All three cores were collected with the track

mounted drilling rig using a direct-push single-tube 2-inch macro core sampling system. The locations of the cores are indicated on Figure 12.

Core 1 was collected in the southern portion of Area 2 in the vicinity of the former aboveground storage tanks. This location coincides with soil-gas point SG-9 and was chosen due to the relatively high concentrations of TPH detected in the 10 ft (586 ppm) and 15 ft (4,433 ppm) soil-gas samples. Soil-gas oxygen concentrations were slightly depleted below ambient atmospheric conditions at both the 10 ft (17.0%) and 15 ft (17.5%) depths.

Core recovery was poor in the upper soil zone from 0 to 2 ft due to the loose and dry nature of the soil. This soil is a black silty loam and is probably non-native backfill in an area that was excavated below the former ASTs. A brown medium-grain sand was located below the surface soil to a depth of 4 ft. Below this sand at 4 ft, a red to red-brown sandy silty clay was encountered and extended to the bottom of the core at 12 ft. This clay is a very stiff, moderately plastic material with very low probability of being capable of transmitting soil gas. No permeable sand zones were encountered. The boring where the core was collected was abandoned by plugging it with hydrated bentonite chips.

Core 2 was collected in the center of Area 3 in the vicinity of the former truck parking/loading circle. This location coincides with soil-gas point SG-10 and was chosen due the relatively low concentrations of soil-gas oxygen detected in the 10 ft (14.5%) and 15 ft (15%) soil-gas samples. The soil-gas hydrocarbon concentrations were only slightly elevated at 10 ft (40.1 ppm) and 15 ft (105.1 ppm).

The surface consists of asphalt pavement that was removed prior to advancing the boring. Core recovery was poor in the upper soil zone from 0 to 2 ft due to the dry compacted nature of the road base material, including very coarse angular gravel, below the asphalt. The material below this consisted of brown medium sand and rapidly graded into a red to red-brown sandy silty clay containing thin zones of white clay with localized medium to coarse sand in the white clay matrix. The clay (both the red and the white zones) is a very stiff, moderately plastic material with very low probably of being capable of transmitting soil gas. No permeable sand zones were encountered. The boring where the core was collected also was abandoned.

Core 3 was collected in the center of Area 1 in the "gravel area" beside the current truck parking/loading area. This location is between soil-gas points SG-7 and SG-8, and was chosen due the presence of a silty sand and a pebble zone indicated on previous cross sections (Figure 12). The hydrocarbon concentrations at SG-8 were only slightly elevated at 10 ft (53.2 ppm) and 15 ft (128.5 ppm).

The surface consists of tightly compacted coarse angular gravel and fine sand that was removed prior to advancing the boring. Core recovery was poor in the upper soil zone from 0 to 2 ft due to the dry compacted nature of the material. The material below this consisted of brown medium sand and rapidly graded into a dark red clay that extended down to 8 ft. This clay is very dense and difficult to drill through. From 8 to 11 ft, a red-brown sandy silty clay was encountered;

from 11 to 13 ft, a pebble zone was encountered. The pebbles were in the medium gravel range and were well rounded. However, the matrix surrounding the pebbles consisted of sandy to silty clay, which severely limits the permeability of the zone. Below 13 ft and extending to the bottom of the boring at 15 ft, a medium-brown sandy-silty clay was encountered. No permeable sand zones were encountered throughout the entire boring.

4.2.1.1 Vent Well Installation. The boring from the collection of Core 3 was overbored with a 4.5-inch hollow-stem auger and completed as a 2-inch, polyvinyl chloride (PVC) soil-gas vent well. The screen was placed from 8 to 14 ft below the surface with a #2 silica sand pack extending to 7 ft bgs. The annulus of the upper 7 ft was plugged with hydrated bentonite chips to the surface. A 2-ft stick-up with a sealed cap was extended above the surface. A vent well diagram is provided in Figure 19.

4.2.1.2 Monitoring Equipment and Installation. Following the installation of vent well VW-1 (see Figure 12), instrumentation was installed to monitor temperature, barometric pressure, and airflow. The data acquisition system is the same setup that was used in the preliminary site testing (NFESC, 2001a). The data were collected and stored in a Hermit 3000 data logger (with an internal barometer). The sensors included an internal barometer, a K-type temperature thermocouple, and a TSI model 8475 airflow transducer. The airflow transducer was powered by a 12-volt battery and the charge was maintained by two solar panels connected through a Sunsaver charge controller. A diagram of the system is shown in Figure 20. Data were collected from April 28, 2002 to May 16, 2002.

4.2.1.3 Sampling Procedures. Soil-gas sampling was performed as described in Section 4.2.1. A grab, soil sample was collected for soil moisture from the cuttings obtained from the installation of the vent well and was sent for analysis to Alpha Analytical, Inc., in Sparks, NV.

4.2.1.4 Analytical Procedures. The soil sample that was collected for soil-moisture analysis was analyzed by U.S. EPA Method 160.3 and the soil moisture was determined to be 12.78%.

4.2.2 Site Characterization Soil Borings at Robins AFB. A single well was advanced to a depth of 6.75 ft with a hand auger at UST Site 2070/2072. The well was located approximately 12 ft west of the existing monitoring well EA2 (Figure 18). The upper soils were local backfill and were comprised of a mixture of sand, silt, and clay typical to the region. The depth to groundwater at the site is approximately 8 ft.

During the hand augering, soils smelled of fuel starting at a depth of ~3 ft bgs and continuing to the total depth of the boring. This is consistent with the documented presence of hydrocarbons at depths to 9 ft bgs (Section 3.2.2.1).

4.2.2.1 Vent Well Installation. The vent well was constructed of 1-inch PVC pipe with a 2-ft-long, 20-slot screen at depths from 4.25 to 6.25 ft bgs. The well had a PVC cap over a 0.5-ft

sump. Solid PVC pipe was installed above the screen, with a riser that extended approximately 1 ft above grade. The well was completed by backfilling the annular space with clean coarse sand to ~4 ft bgs, followed by natural fill, hydrated bentonite, and a mix of natural fill and bentonite. A diagram of the well is presented in Figure 21.

4.2.2.2 Monitoring Equipment and Installation. Monitoring equipment was attached to the well to measure absolute ambient pressure (Vaisala Model PTB 101B), differential pressure (Ashcroft Model XLdp), airflow (TSI Model 40241), temperature (Type T thermocouple), and battery voltage. The monitoring system was installed in a vented plastic box through which two tubes were run. The first was a 0.25-inch outside diameter (O.D.) high-density polyethylene tube (0.125-inch inside diameter [I.D.]) attached from the wellhead to the pressure sensors. The second tube was a 1.0-inch O.D. Tygon® tube from the 1-inch O.D. PVC well to the flowmeter and subsequently to a magnetic latching valve (Skinner Model 12 volts, direct current, ¼-inch orifice). The magnetic latching valve was used to periodically block flow through the system in order to allow accurate measurements of the subsurface pressure. The valve was selected because it requires no power to be maintained in either the open or closed position. A small amount of power was consumed during the switching process.

Temperature, pressure, airflow, and battery voltage data were collected every 15 minutes, beginning on the hour, and was logged on a Campbell CR10X data logger. The CR10X logger was capable of controlling instruments as well as data logging and was used with a relay driver (Campbell Model A12REL-12) to switch the magnetic latching valve. Between the 15-minute full data collection intervals, the magnetic latching valve was closed for 2 minutes and subsurface pressure data were collected. The valve was normally open to allow unimpeded flow between the subsurface (through the well) and the surface. It was closed for brief intervals to measure pressure in the subsurface (using the differential and absolute pressure sensors).

The monitoring system was contained in a vented weatherproof box (Rubbermaid) and was powered by a deep cycle, 12-volt battery (Chairman Model PVC-1248) charged by a 75-watt photovoltaic panel (Siemens Model SP75). The solar charging cycle was moderated by a charge controller with automatic low voltage disconnect (Morningstar Model Sunsaver 6-LVD) to protect the battery.

4.2.2.3 Sampling Procedures. Soil-gas measurements of oxygen and carbon dioxide were made using a LandTec GA 90 at the beginning and end of the monitoring effort. Soil gas was sampled directly from the newly installed vent well using the internal pump of the GA 90. Initial baseline measurements made in the sealed well, prior to passive bioventing, were recorded after 5 minutes of sampling (approximately 1-L/min flow). At the end of the two-week test, gas in the well again was measured and results were recorded after 20 minutes of sampling, when measurements had reached a steady state. No hydrocarbon soil-gas measurements were made.

4.2.2.4 Analytical Procedures. No soil samples were collected and submitted for soil-moisture analysis from Robins AFB Site 2070/2072.

5. Performance Assessment

5.1 Performance Data

5.1.1 Fort Stewart Airflow Data. A data acquisition system was set up and connected to soil-gas vent well VW-1 at SWMU 35, Fort Stewart. Barometric pressure, temperature, and flow data were collected at 10-minute intervals for a period of 2½ weeks. The data then were downloaded to a laptop computer and formatted for analysis. The results are graphed in Figure 22. As indicated on the graph, the barometric pressure changes in response to two phenomena. The large fluctuations are a result of weather fronts passing through the area. Superimposed on the large fluctuations is a pattern of smaller variations created by diurnal changes in the density of the atmosphere caused by the daily warming effect of the sun. The combined large and small changes in barometric pressure drive passive bioventing by creating a differential pressure between the soil gas and the atmosphere. In theory, in response to these changes, the vent well should provide a conduit for air to move in or out of the soil. However, at the Fort Stewart site, the low permeability of the soil (discussed in Section 4.2) restricted the flow to a rate that is below the range of the flow transducer. The flows indicated in Figure 22 are below the lower range (10 ft/min, or 0.30 cfm equivalent in a 2-inch-diameter pipe) of the TSI transducer. The performance of the flow transducer is discussed at length in the flow calibration investigation presented in Appendix C. The flows indicated in Figure 22 are comparable to flows recorded in the field in a blank section of pipe that had the bottom tightly capped. The spikes in the data correspond to minima in the daily temperature changes indicated in Figure 22. This correlation also was noted in the calibration field test. Therefore, the calibration data indicate that flows which are <0.30 cfm are not real and are artifacts of “noise” in the system. These flows also are significantly below the practical design criteria of a maximum peak daily airflow rate of 1 cfm, as stated in the Technology Demonstration Plan (TDP) (NFESC, 2001b).

The results of the field test on vent well VW-1 indicate that no significant (i.e., measurable) airflow occurs in the vent well as a result of barometric pressure changes. Passive-driven bioventing was not occurring, and, given the soil conditions encountered at the site, even bioventing augmented with a powered blower would probably be of limited effectiveness due the low permeability of the soil. Most of the soil-gas monitoring points, groundwater monitoring wells, and the vent well at the site did not yield soil gas even under high vacuum (15-20 inches water). Therefore, the desired design criteria cannot be met given the soil conditions at the site.

5.1.2 Robins AFB Site Characterization Data. Soil-gas samples, from the well casing, were collected following the well installation at Robins AFB. Oxygen and carbon dioxide levels were 0.2% and 11.4% respectively. These concentrations would indicate that oxygen-limiting conditions existed at the test site. Following two weeks of passive bioventing activities, the oxygen in the well had increased to 3.0% and the carbon dioxide had been diluted to 10.2%.

Atmospheric pressure, temperature, and corresponding airflow rates into the vent well at Site 2070/2072 were collected at 15-minute intervals from February 11, 2002 to February 18, 2002. The data are presented in Figure 23. The data indicate that diurnal fluctuations in temperature

occurred as expected. Although no major storm fronts occurred during the monitoring period, measurable barometric pressure changes should have permitted some level of airflow into the vent well. The airflow data, however, indicate very low flowrates during this period. With maximum flows of <0.1 cfm, and noticeable periods of no flow, the overall air movement into the subsoil was minimal. The indicated flows may even be below the reporting limit confidence for the flow sensor. Again, these flowrates are significantly below the TDP criteria (NFESC, 2001b) for maximum peak airflow rates.

5.2 Data Assessments and Recommendations for Ft. Stewart and Robins AFB

Several weeks of testing were conducted at sites at Fort Stewart and Robins AFB to investigate their potential of conducting an extended passive bioventing demonstration. Diurnal and weather-related influences were recorded that did cause barometric pressure cycles with sufficient amplitude to generate pressure differentials between the atmosphere and the subsurface soils. However, it appears that the subsurface at both sites did not sufficiently delay the surface pressure signal to cause differentials that would promote and sustain the movement of oxygen into the soil via the vent well. All preliminary tests revealed that the differential pressures that were driving barometric flow were too low to induce a satisfactory volume of oxygen to move into the contaminated soils that are indigenous to each site. Additionally, the soil cores collected at Fort Stewart indicated that soil permeability was likely too low for passive bioventing to be effective.

The maximum flowrates measured at Fort Stewart and Robins AFB were below 0.3 scfm (Figures 22 and 23). With a TDP performance criteria specification for maximum airflow rates on the order of 1 cfm, it is apparent that the conditions at Fort Stewart and Robins AFB are not conducive to an extended testing effort. It is therefore recommended that no long-term demonstration of natural pressure driven passive bioventing be performed at these sites. Additionally, because these sites were identified as the best candidates for the demonstration (NFESC, 2001a), it is recommended that no additional effort be made to identify potential sites and that the demonstration phase of this project not be performed.

5.3 Technology Comparison

The most valid technology comparison for passive bioventing is to conventional, active bioventing. Given the similarities between the two technologies and the historical cost-effectiveness of conventional bioventing, passive bioventing can only be considered as an alternative to conventional bioventing rather than compared against other technologies.

Airflow rates and the resulting radius of influence for passive versus conventional bioventing are the parameters for evaluating the success of each technology and comparing the two technologies. In order to perform a definitive comparison between the two technologies, it would be necessary to have conventional bioventing data for the specific study sites at Fort Stewart and Robins AFB. Historical bioventing data for these sites do not exist and was to be generated as a component of the long-term demonstration. The passive bioventing technical performance criteria were not achieved during the site characterization efforts and no recom-

mendation was made for a long-term demonstration, so no active bioventing data were generated at either site. Therefore, this comparison is not presented.

6. Cost Assessment

6.1 Cost Performance

Technical performance criteria were not achieved during the site characterization efforts and no recommendation was made for a long-term demonstration, so no cost performance evaluation was prepared.

6.2 Cost Comparison to Conventional and Other Technologies

Technical performance criteria were not achieved during the site characterization efforts and no recommendation was made for a long-term demonstration, so no cost comparison to other technologies was prepared.

7. Regulatory Issues

Technical performance criteria were not achieved during the site characterization efforts and no recommendation was made for a long-term demonstration, so no approach to Regulatory Compliance and Acceptance was prepared.

8. Technology Implementation

8.1 DoD Need

The need still exists for cost-effective technologies to address the approximately 2,000 DoD sites that may have petroleum, oils, and lubricant (POL) contamination (U.S. EPA, 1997). However, based on the limitations of employing passive bioventing at sites with shallow groundwater and limited vadose zones, passive bioventing does not appear to be a viable option to address this existing need at sites with these characteristics.

8.2 Transition

Based on the inability to identify a site with shallow groundwater and a limited vadose zone that permitted achieving the performance criteria established and in the approved Technical Demonstration Plan and its Addendum, it is not recommended that passive bioventing be applied to shallow-groundwater DoD sites with characteristics similar to those encountered during these characterization activities.

9. Lessons Learned

The following lessons were learned during the site-investigation activities that were designed to identify a site for the long-term demonstration of natural pressure-driven passive bioventing:

1. Shallow vadose zones limit the movement of air into the soil via passive bioventing. Based on the most recently collected data, there is very limited barometric pumping of ambient air into shallow vadose zones via vent wells. The differential pressure between the atmosphere and the subsoil appears to be too small to promote substantial airflow rates though the well system, which is required for an economical application of this technology. It is assumed that sites with shallow vadose zones that have certain lithologic features (i.e., sandy soils overlain by impermeable lenses) may promote passive bioventing.

2. Site applicability for passive bioventing may be limited. The short-term passive bioventing investigations that preceded this site-characterization phase looked at 10 potential sites. Of these 10 sites, two were recommended for additional site characterization efforts (NFESC, 2001a). Eventually, those two best candidates did not meet the performance criteria to permit recommending a long-term demonstration of the technology. This indicates that the number of sites with shallow groundwater that would benefit from passive bioventing would be limited.

Based on these critical observations, the application of passive bioventing in shallow vadose zones apparently is not viable, especially in climatic regions similar to the eastern United States, and is not recommended as an economical option to active bioventing at similar sites.

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Appendix A
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Appendix B
Data Archiving and Demonstration Plan

Electronic data from the site investigation activities have been included in Appendix D, including data from the monitoring as well as an electronic version of this report.

A copy of the technology demonstration plans and all other supporting material can be obtained by contacting either the principal investigator or the external contractor point-of-contact listed in Appendix A.

Appendix C
Calibration Verification of TSI Model 8475 Air Velocity Transducer

Background

In July 2002 an investigation was conducted to determine the status of the TSI Model 8475 air velocity transducer used in Natural Pressure-Driven Passive Bioventing field study at Fort Stewart, GA. The investigation was designed to determine if the transducer was functioning correctly and that it was producing results that were in accordance with the performance criteria stated by the equipment manufacturer. The investigation was conducted in three steps. The first step was to determine if the instrument was generally functioning correctly throughout the entire operating range using a calibrated wind tunnel. The second step involved verifying the calibration at low flowrates using a computer-controlled mass flow controller in conjunction with a calibrated volumetric measuring device. The final step involved a short field test under "typical" field conditions with a capped pipe to simulate a no-flow condition, similar to the conditions at Fort Stewart.

Principle of Operation

The TSI Model 8475 air velocity transducer consists of a small (approximately ⅛-inch-diameter) probe and a electronic control module that are connected by a thin electrical cable. The control unit is powered by a low voltage (11 to 30 V) DC power supply. Flow measurements are obtained by measuring the amount of power required to maintain a constant temperature in the tip of the probe. Air flowing past the tip of the probe provides cooling that is proportional to the velocity of the air. Thus, higher airflow rates require greater amounts of power to maintain the constant temperature at the tip. The control unit automatically compensates the measured velocity for the ambient temperature of the air using a separate electronic circuit in the tip of the probe. This allows the unit to perform measurements under a wide range of temperatures. The compensated range is 32 to 140°F (TSI, Inc., 2000). Measurements are omni-directional and do not include a directional vector. The control unit uses a selectable time constant to average the instantaneous flow velocities. The control unit then displays the velocity on an internal LCD display and simultaneously outputs a constant current signal corresponding to the resulting velocity. The external signal is scaled to 4-20 mA across the range of the instrument. All testing was performed with the instrument scaled for 0 to 300 ft/min measurements (equivalent to 0 to 6.87 cfm in 2-inch-diameter polyvinyl chloride [PVC] pipe). The calibrated external signal is thus expected to be scaled from 4 mA at 0 ft/min flow and 20 mA at 300 ft/min flow. The signal is updated every 10 seconds, according to the selected time constant for this work. The output signal is then electronically scaled and automatically recorded by an external data recorder. A conversion from the flow velocity (as measured and recorded) to volumetric flow in cubic feet per minute (cfm) is performed on the data after it is downloaded from the recorder.

Wind Tunnel Investigation
The overall performance of the air velocity transducer was evaluated using a calibrated wind tunnel (TSI model 8390) in the flow calibration laboratory at Battelle in Columbus, OH. The wind tunnel, shown in Figure C-1, is calibrated and maintained by personnel from the instrument calibration laboratory and is frequently used for calibrating similar instruments. A variable-speed fan powers the wind tunnel. Interchangeable flow plates are used to select the desired flow range. The range of operation for the wind tunnel is approximately 30 ft/min to greater than 500 ft/min. A digital display indicates the flow across the plate as measured by a very sensitive differential pressure transducer. A sealed access port allows the transducer to be inserted into the flow in the center of the wind tunnel.

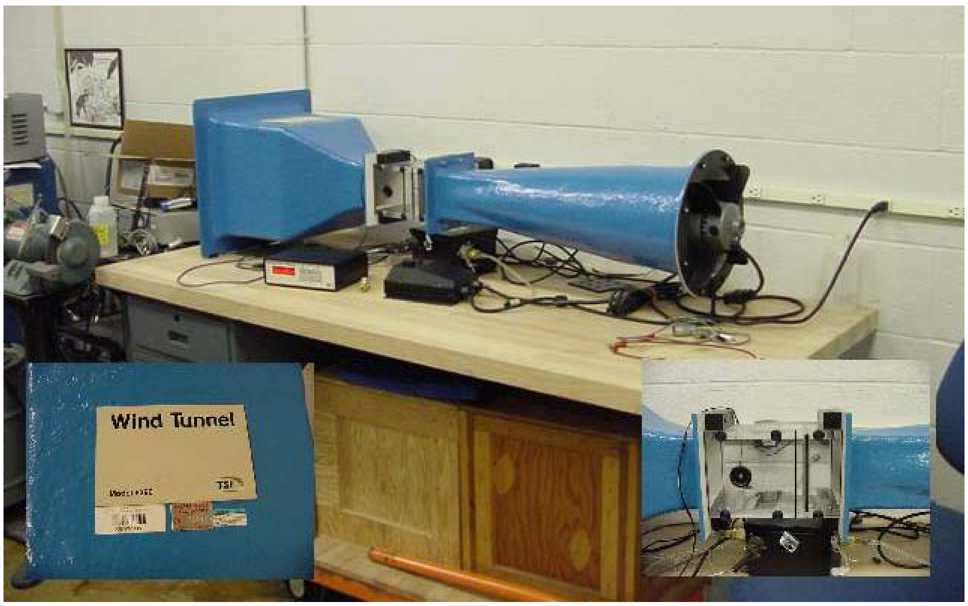

Figure C-1. TSI Wind Tunnel

The flow range of the wind tunnel is greater than the velocities typically encountered in passive bioventing, but the device allowed the overall performance of the transducer to be evaluated. Testing involved flow velocities from 30 to 500 ft/min (equivalent to 0.69 to 11.45 cfm in 2-inch-diameter PVC pipe). The results of the wind tunnel test are shown in Table C-1. Readings also were recorded and plotted to test the response of the instrument with no flow. A digital multimeter was used to independently measure the 4 to 20 mA output signal of the transducer, and the results are included in the table. Three runs were made to test the operation over the entire range of velocities. Where possible, overlapping measurements were made within the ranges.

Results from the testing indicate that the air velocity transducer is functioning correctly in the range of 30 to 300 ft/min. When the velocity exceeded approximately 325 ft/min (equivalent to

Table C-1. TSI Flow Transducer Response to Calibrated Flow in TSI Model 8390 Wind Tunnel

Calibrated Flow (ft/min)	Run #	TSI Internal Display (ft/min)	mA Output Signal	Hermit Display (ft/min)	Equivalent Flow in 2 inch Schedule 40 PVC Pipe (cfm)	Comments
0	1	0.0	4.00	–0.156	0.00	
0	2	0.0	4.00	–0.154	0.00	
30	1	31.1	5.65	30.578	0.69	
60	1	59.0	7.14	58.792	1.37	
90	1	87.2	8.63	86.465	2.06	
120	1	115.0	10.12	114.895	2.75	
150	1	142.4	11.58	141.230	3.44	
150	2	150.5	12.01	149.922	3.44	
200	2	195.7	14.42	194.969	4.58	
250	3	242.3	16.92	241.622	5.73	
250	3	244.5	17.00	242.369	5.73	
300	3	287.2	19.32	286.891	6.87	
320	3	300.5	20.00	300.410	7.33	
325-330	3					Upper limit of output range
350	3	OVER	21.02	308.729	8.02	
400	3	OVER	21.02	308.730	9.16	
500	3	OVER	21.02	308.731	11.45	

Run # 1- Initial calibration 0 to 150 ft/min.
Run # 2 - 50-250 ft/min flow plate.
Run # 3 - 250-500 ft/min flow plate.

7.44 cfm in 2-inch-diameter PVC pipe) the internal LCD indicated the flow as “OVER” indicating the maximum measurement limit was reached. The external output signal remained constant at 21.02 mA at all velocities above 325 ft/min. The results of the measurements are plotted in Figure C-2. The small offset in the center of the graph indicates a shift in the response due to repositioning the sensor as the flow plates were changed to allow the higher velocities to be measured. Also, the output becomes slightly non-linear at 300 to 325 ft/min (equivalent to 6.87 to 7.44 cfm in 2-inch-diameter PVC pipe) at the upper end of the flow range.

During the wind tunnel test, the sensitivity of the instrument to the supply voltage was investigated to determine if variability of the battery voltage in the field might have affected the measurements. The supply voltage was varied between 11 and 16 V and the effects were observed. The instrument correctly compensated for the variability in the range of input voltage, by holding a constant output signal of 19.17 mA ±0.03 mA with the applied velocity held constant at 300 ft/min in the wind tunnel. However, it was observed that the input current to the transducer increased as the voltage decreased. This was expected, because the power required to heat the tip at a constant flowrate is also constant (power, in watts, = voltage × current). When the input voltage was reduced to approximately 10.3 to 10.5 V the transducer indicated “LO VOLT” on the internal display, and the external output was switched off (no signal).

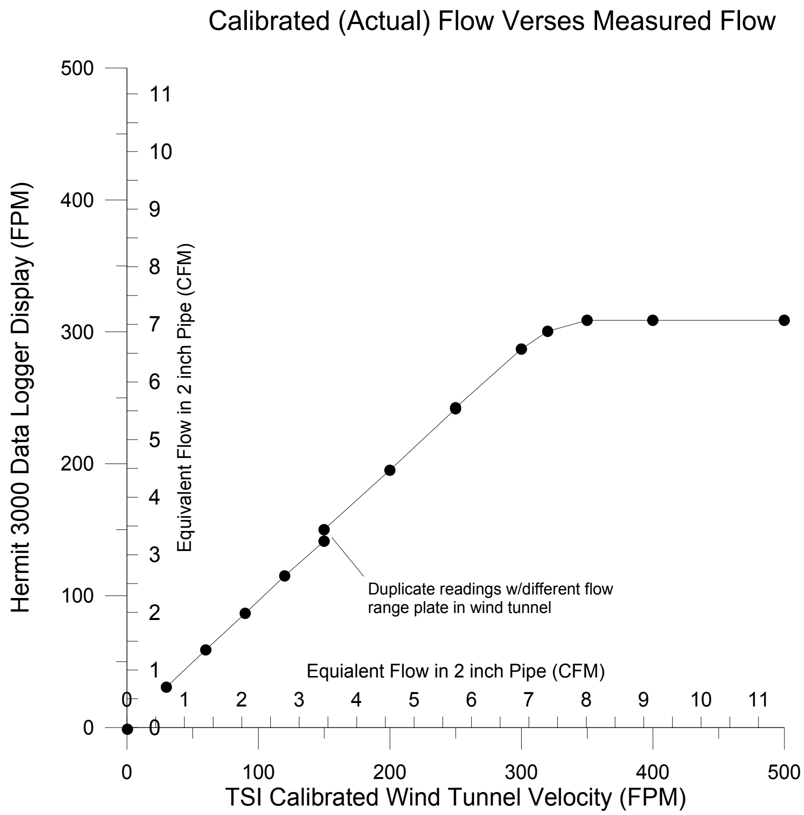

Figure C-2. Results of Wind Tunnel Test

Results of testing in the wind tunnel indicate that (1) the transducer functions correctly in 30 to 300 ft/min range (equivalent to 0.69 to 6.87 cfm in a 2-inch-diameter PVC pipe), (2) the output signal reaches a steady maximum value of 21.02 mA (308.7 ft/min on the data logger) at approximately 325 ft/min (equivalent to 7.44 cfm in 2-inch-diameter PVC pipe), (3) at zero flow the data logger records a slightly negative result, but the internal display and the external output indicate no flow (4 mA output), and (4) the instrument functions correctly in the 11 to 16 V range and terminates output below about 10.5 V.

Mass Flow Controller Investigation

A mass flow controller was used to investigate the performance of the TSI Model 8475 air velocity transducer at low flowrates. The flow controller contains a precision, calibrated orifice used in conjunction with a precision control valve to maintain a steady flow of gas. A highly sensitive differential pressure transducer is used to determine the flow, and a digital flow controller is used to select and maintain a highly accurate flowrate. This instrument is routinely used to calibrate other flow instruments. In order to maintain the calibration of the flow controller, analytical grade nitrogen is used instead of air. The mass flow control module and the digital flow controller are shown in Figure C-3.

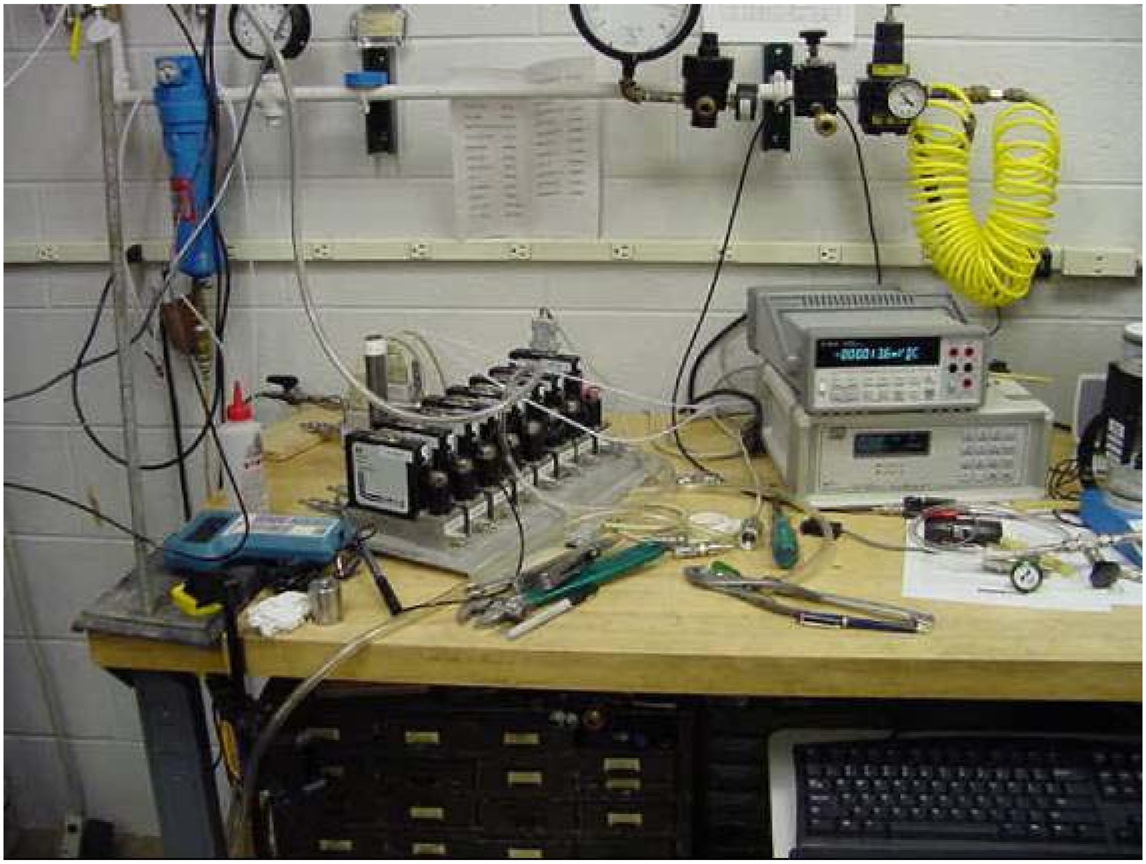

Figure C-3. Mass Flow Controller

In conjunction with the mass flow controller, a calibrated bell prover was used to independently measure the flow. The bell prover is a large (5 ft^3) inverted copper bell that is submerged in an oil bath inside a large iron tank. The copper bell is suspended with a counter weight and is held in the center of the iron tank with low friction guides. The bell is graduated on the outside so that the amount of gas contained in the bell is accurately indicated. The flow in cfm is determined by timing the displacement of gas into the bell. A schematic diagram of the test setup in shown in Figure C-4. Results of the test indicated the flow from the mass flow controller and the volume recorded in the bell prover agreed to within 3%. Figure C-5 shows the setup of the test with the bell prover and the TSI air velocity transducer tip inserted into a vertical section of 2-inch-diameter PVC pipe. All calibrated flow measurements are thus in cfm instead of ft/min (as in the wind tunnel) and the flows were converted into a resulting velocity by dividing by the sectional area of the pipe. A table showing resulting flow velocities for various cfm in several standard pipe diameters is shown in Table C-2.

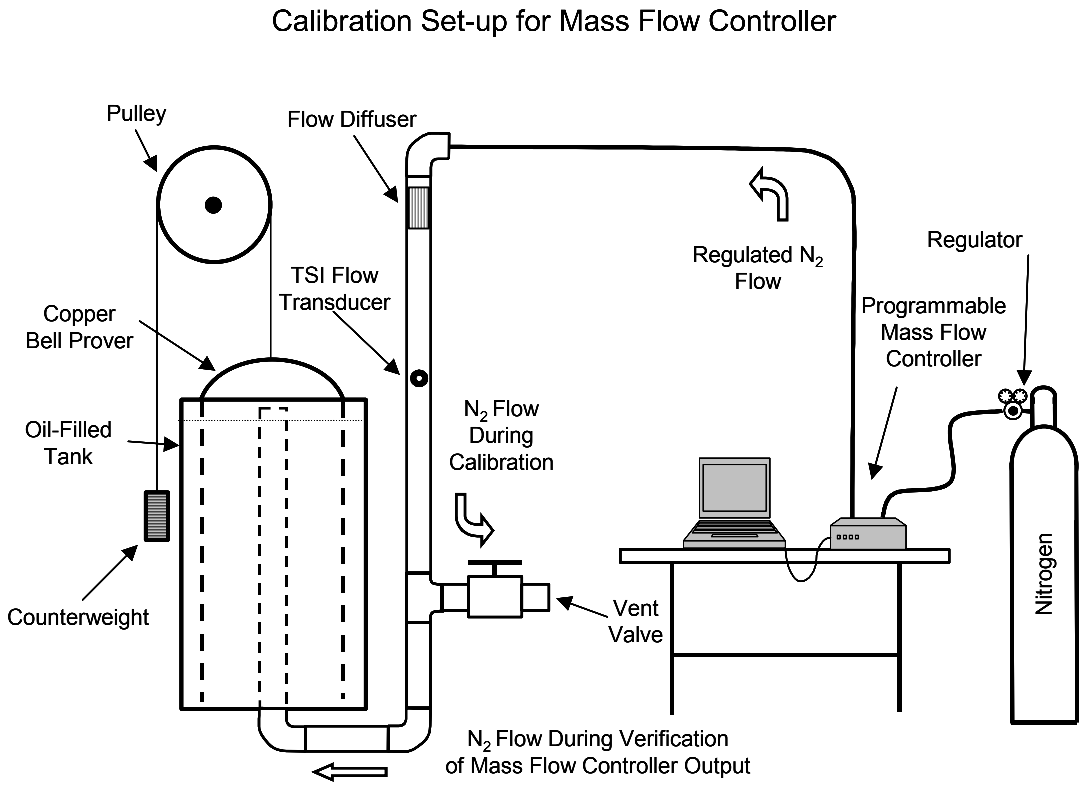

Figure C-4. Calibration Setup for Mass Flow Controller

Three trial runs were performed using the apparatus described above. During each run the flow was progressively decreased in a stepwise manner and measurements of the results at each step were recorded. Table C-3 indicates the flow and the resulting instrument output for flows ranging from 0.7 cfm to 0.05 cfm (30 to 2 ft/min) for each of the three trials. The transducer tip was removed and reinserted into the PVC pipe following each trial to determine if placement of the transducer tip in the pipe affected the measurement. A graph of the output as recorded by the data logger for each of the trials is shown in Figure C-6.

Results of the measurements indicate that placement of the probe tip in the pipe does slightly affect the measurement by approximately ±0.2 cfm. More significantly, however, the results indicate that the lower limit of the velocity transducer is approximately 0.25 to 0.30 cfm, depending on the placement of the probe tip. This corresponds to a flow velocity of approximately 10 ft/min and agrees with the manufactures stated range of 10 ft/min to X , where X is the selected maximum range of the transducer. Therefore, the lowest output of the velocity transducer is approximately 10 ft/min (0.23 cfm in a 2-inch-diameter PVC pipe) and corresponds to an output current of 4 mA. As observed in the wind tunnel tests, a zero flow condition produces a very slightly negative value on the data logger due to processing of the signal between the TSI air velocity transducer and the logger.

Figure C-5. Bell Prover with TSI Air Velocity Transducer

Field Evaluation of the TSI Air Velocity Transducer
A short field test was performed on the TSI air velocity transducer and the data logger to evaluate the combined effects of "typical" field conditions on the transducer response and the resulting recorded data. In addition to flow, the temperature in the data recorder enclosure and the absolute barometric pressure were also recorded. The air velocity transducer was assembled in a 4 ft length of 2-inch-diameter PVC pipe with a 180-degree bend at the top to prevent rain from entering. This configuration was identical to the arrangement used in the field test at Fort Stewart. In this case, however, the bottom of the pipe was sealed with an airtight cap to prevent flow from occurring in the pipe. The logger was powered by a 12 V car battery that was charged by the same solar panels and charging controller that was used in the field. The logger was set to collect readings every 10 minutes and the duration of the test was approximately 7 days.

Table C-2. Flow Velocity (ft/min) in Pipes of Selected Diameters

Pipe Diameter (inches)		**1.25**	**1.5**	**2**	**2.5**	**3**	**4**
Area (ft^2)		**0.010**	**0.014**	**0.023**	**0.033**	**0.050**	**0.087**
Flow Volume (cfm)	0.05	4.93	3.62	2.18	1.53	0.99	0.57
	0.1	9.85	7.23	4.37	3.07	1.98	1.15
	0.2	19.71	14.47	8.73	6.13	3.96	2.29
	0.3	29.56	21.70	13.10	9.20	5.94	3.44
	0.4	39.42	28.94	17.47	12.27	7.93	4.59
	0.5	49.27	36.17	21.84	15.34	9.91	5.74
	0.6	59.13	43.40	26.20	18.40	11.89	6.88
	0.7	68.98	50.64	30.57	21.47	13.87	8.03
	0.8	78.84	57.87	34.94	24.54	15.85	9.18
	0.9	88.69	65.11	39.30	27.60	17.83	10.32
	1	98.55	72.34	43.67	30.67	19.81	11.47
	2	197.09	144.68	87.34	61.34	39.63	22.94
	3	295.64	217.02	131.01	92.01	59.44	34.41
	4	394.19	289.37	174.68	122.68	79.25	45.88
	5	492.74	361.71	218.35	153.35	99.07	57.35
	6	591.28	434.05	262.02	184.02	118.88	68.82
	7	689.83	506.39	305.69	214.69	138.69	80.29
	8	788.38	578.73	349.36	245.36	158.51	91.76
	9	886.92	651.07	393.03	276.03	178.32	103.24
	10	985.47	723.41	436.71	306.70	198.13	114.71
	11	1,084.02	795.75	480.38	337.37	217.94	126.18
	12	1,182.57	868.10	524.05	368.04	237.76	137.65
	13	1,281.11	940.44	567.72	398.71	257.57	149.12
	14	1,379.66	1,012.78	611.39	429.38	277.38	160.59
	15	1,478.21	1,085.12	655.06	460.05	297.20	172.06
	16	1,576.75	1,157.46	698.73	490.72	317.01	183.53
	17	1,675.30	1,229.80	742.40	521.39	336.82	195.00
	18	1,773.85	1,302.14	786.07	552.06	356.64	206.47
	19	1,872.39	1,374.49	829.74	582.73	376.45	217.94
	20	1,970.94	1,446.83	873.41	613.40	396.26	229.41

Results of the field evaluation are shown in Figure C-7. The graph indicates that the logger records very small spikes of "positive values" that occur on a daily cycle. These spikes seem to occur during the period from mid-morning to mid-afternoon each day. However, these values are below the 0.30 cfm threshold described in the preceding section as the lower limit of the air velocity transducer output. Therefore, it must be concluded that the "positive values" indicated on the flow graph in Figure C-7 are noise and should be filtered from the data. This noise also is present in the data collected at the two field sites (Fort Stewart and Robins AFB) presented in the Figures 22 and 23 of Section 5 of the main report.

Table C-3. TSI Flow Transducer Response to Flow in 2-Inch Schedule 40 PVC Pipe Regulated by a Mass Flow Controller

Replicate	Calibrated Flow (cfm)	TSI Internal Display (ft/min)	mA Output Signal	Hermit Display (ft/min)	Corresponding Velocity in 2 inch Schedule 40 PVC Pipe (ft/min)	Comments
1	0.7000	27.0	5.43	27.456	30.568	
1	0.5000	16.6	4.88	16.452	21.834	
1	0.4000	11.7	4.62	11.403	17.467	
1	0.3500	8.9	4.47	8.631	15.284	Lower limit of output range
1	0.3000	1.1	4.06	0.914	13.100	
1	0.2500	0.0	4.00	–0.172	10.917	
1	0.2000	0.0	4.00	–0.152	8.734	
1	0.1500	0.0	4.00	–0.171	6.550	
1	0.1000	0.0	4.00	–0.152	4.367	
1	0.0500	0.0	4.00	–0.151	2.183	
2	0.7000	36.6	5.95	36.654	30.568	
2	0.5000	24.0	5.28	23.739	21.834	
2	0.4000	17.9	4.95	17.709	17.467	
2	0.3500	15.1	4.80	14.762	15.284	
2	0.3000	11.6	4.62	11.408	13.100	
2	0.2500	7.2	4.38	6.870	10.917	Lower limit of output range
2	0.2000	0.0	4.00	–0.169	8.734	
2	0.1500	0.0	4.00	–0.169	6.550	
2	0.1000	0.0	4.00	–0.169	4.367	
2	0.0500	0.0	4.00	–0.150	2.183	
3	0.7000	27.9	5.49	27.737	30.568	
3	0.5000	17.1	4.91	16.933	21.834	
3	0.4000	12.0	4.66	12.086	17.467	
3	0.3500	9.6	4.50	9.330	15.284	Lower limit of output range
3	0.3000	2.8	4.15	2.468	13.100	
3	0.2500	0.0	4.00	–0.150	10.917	
3	0.2000	0.0	4.00	–0.169	8.734	
3	0.1500	0.0	4.00	–0.150	6.550	
3	0.1000	0.0	4.00	–0.150	4.367	
3	0.0500	0.0	4.00	–0.149	2.183	

The source of the noise cannot be identified with certainty, but may be electrical interference from other equipment in the recorder enclosure. The noise in the data from Robins AFB has much lower amplitude than the other data sets and is probably because the data was collected by different equipment. The data from the closed pipe field test and the Fort Stewart field test look

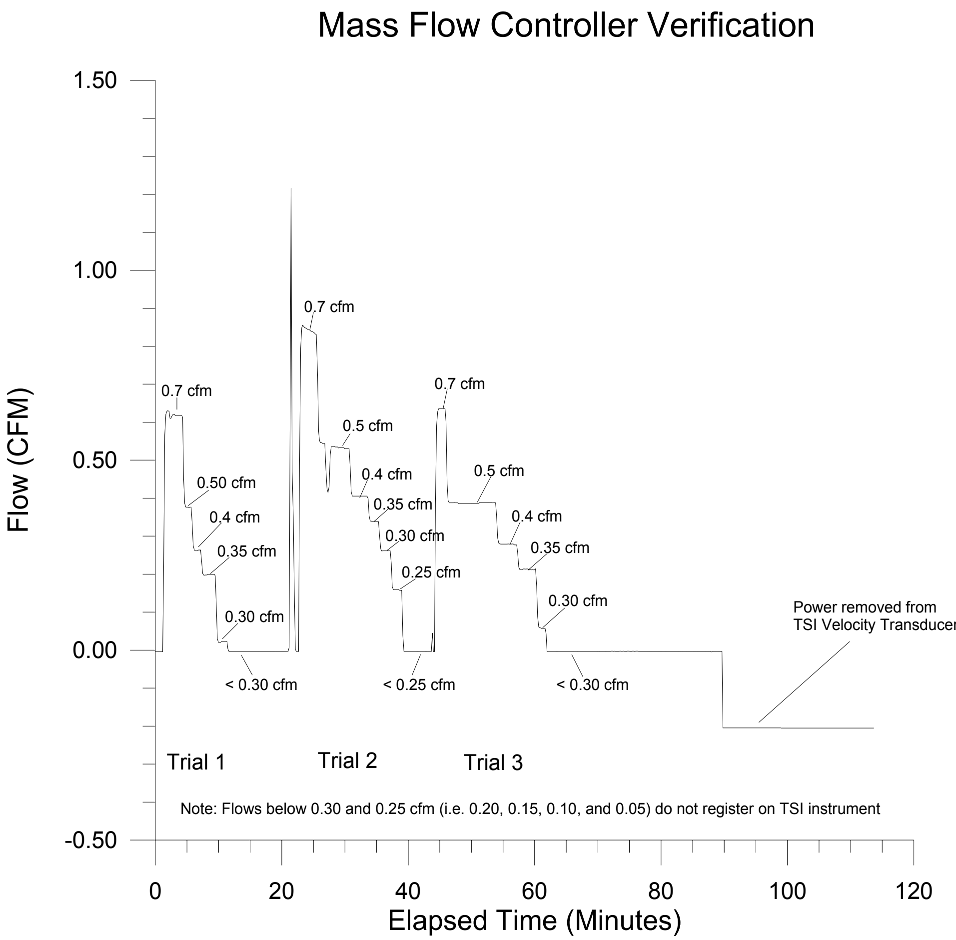

Figure C-6. Results of Mass Flow Controller Test

very similar and were collected with the same equipment. Several observations can be made regarding the noise: (1) it seems to occur during the period from mid-morning to mid-afternoon each day, (2) it does not occur at night, (3) the amplitude of the noise varies slightly and in the Fort Stewart data, mimic the barometric pressure, and (4) the length of the period of noise each day at Fort Stewart is slightly longer than in the closed pipe test. This indicates that the noise is occurring during the daytime when the temperature is at a daily maximum and the solar panels would be receiving the maximum sunlight. The third point is important, because it would indicate that the noise is proportional to the amount of sunlight (assuming high barometric pressure indicated clear weather, and lower pressure indicated more cloud cover). The fourth point is also important, because the horizon at Fort Stewart was considerably wider than the horizon at the closed pipe test sight, and the solar panels received direct sunlight for a longer period each day. It is likely that the solar panel/battery controller is the source of the electrical noise. The controller probably generates the noise due to its regulation of the charging of the battery when the solar panels are providing power. The noise may be radiated to the logger through unshielded signal wiring, or transmitted to the air velocity transducer through the 12 V power supply.

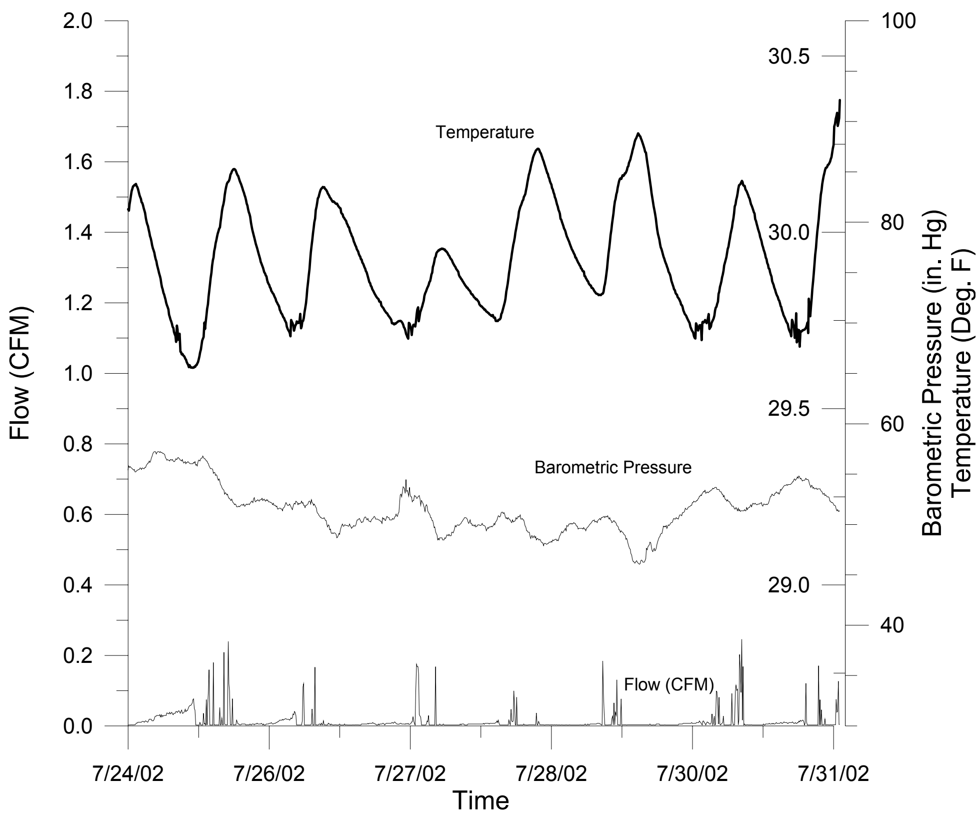

Figure C-7. Results of Field Calibration Test

The final conclusion of the calibration verification of the TSI air velocity transducer is that the transducer is functioning correctly and provides reasonably accurate flow velocities *within the stated range of the instrument*. However outside of the range of 9 to 300 ft/min (0.30 to 7 cfm in 2-inch-diameter PVC pipe) the transducer cannot provide meaningful results.

Reference

TSI, Inc. 2000. Model 8455/8465/8475 Air Velocity Transducer Operation and Service Manual. TSI Incorporated 500 Cardigan Road, Shoreview, MN 55126. 28p.

Appendix D
Electronic Data Summary and Report File

Included in this Appendix is a CD-ROM (IBM format) which contains electronic data files for the site characterization activities and an electronic copy of this report. The following files can be found on the CD-ROM:

Name	Description	File Format
CLOSED PIPE DATA.XLS	Calibration Field Test Data	Microsoft® Excel
FT STEWART DATA.XLS	Fort Stewart Field Test Data	Microsoft® Excel
ROBINS AFB DATA.XLS	Robins AFB Field Test Data	Microsoft® Excel

Table 1. Fort Stewart Natural Pressure Driven Passive Bioventing Study Soil Gas Samples

Date	Location	Depth/Screen	O_2 (%)	CO_2 (%)	TPH (ppm)	FID (ppm)	Comments
04/22/2002	Soil Gas Point #1	5	20.5	0.05	23	0.0	Vacuum pump sample
		10	20.9	0.0	0	2.5	Vacuum pump sample
		15	20.8	0.05	56	96.4	Vacuum pump sample
04/27/2002	Soil Gas Point #1 (Hand Driven)	5	18.0	4.5	60	5.6	Hand bulb sample
		10	NR	NR	NR	NR	Hand bulb sample
04/22/2002	Soil Gas Point #2	5	20.9	0.0	3	0.0	Vacuum pump sample
		10	20.9	0.0	24	40.4	Vacuum pump sample
		15	20.9	0.05	20	14.2	Vacuum pump sample
04/22/2002	Soil Gas Point #3	5	20.9	0.0	0	0.0	Vacuum pump sample
		10	20.9	0.0	2	0.0	Vacuum pump sample
		15	20.9	0.0	5	0.0	Vacuum pump sample
04/27/2002	Soil Gas Point #3 (Hand Driven)	5	20.0	0.0	10	3.2	Hand bulb sample
		10	20.5	0.5	37	0.0	Hand bulb sample
04/23/2002	Soil Gas Point #4	5	20.9	0.0	0	0.0	Vacuum pump sample
		10	20.9	0.0	31	0.0	Vacuum pump sample
		15	20.9	0.5	34	8.2	Vacuum pump sample - water in sample
04/27/2002	Soil Gas Point #4 (Hand Driven)	5	20.9	0.0	17	0.0	Hand bulb sample
		10	20.9	0.0	0	0.0	Hand bulb sample
04/23/2002	Soil Gas Point #5	5	20.9	0.05	4	0.0	Vacuum pump sample
		10	20.9	0.5	40	11.5	Vacuum pump sample
		10 dup	20.9	0.0	20	7.6	Vacuum pump sample - 3 min. purge
		10 dup	20.9	0.0	15	2.4	Vacuum pump sample - 7 min. purge
04/23/2002	Soil Gas Point #6	5	NR	NR	NR	NR	Hand bulb sample
		10	20.9	0.0	190	123.3	Hand bulb sample
		10 dup	20.4	0.0	920	468	Hand bulb sample - 1 hour later
04/23/2002	Soil Gas Point #7	5	20.0	1.5	44	1.2	Hand bulb sample
		10	20.0	1.5	40	0.0	Hand bulb sample
		15	20.0	1.5	1900	25.5	Hand bulb sample
04/23/2002	Soil Gas Point #8	5	NR	NR	NR	NR	Hand bulb sample
		10	20.5	1.0	2900	52.3	Hand bulb sample
		15	20.0	1.3	1600	128.5	Hand bulb sample
04/23/2002	Soil Gas Point #9	5	19.0	8.0	62	5.3	Hand bulb sample
		10	17.0	12.0	1400	586.0	Hand bulb sample
		15	17.5	8.0	2300	4433	Hand bulb sample

Table 1. Fort Stewart Natural Pressure Driven Passive Bioventing Study Soil Gas Samples (continued)

Date	Location	Depth/Screen	O_2 (%)	CO_2 (%)	TPH (ppm)	FID (ppm)	Comments
04/24/2002	Soil Gas Point #10	5	18.2	7.5	190	9.7	Hand bulb sample
		10	14.5	11.5	670	40.1	Hand bulb sample
		15	15.0	10.8	880	105.1	Hand bulb sample
04/24/2002	Soil Gas Point #11	5	16.0	9.0	175	28.2	Hand bulb sample
		10	17.5	7.0	1600	51.6	Hand bulb sample
		15	16.0	9.5	540	52.6	Hand bulb sample
04/24/2002	Soil Gas Point #12	5	19.0	6.0	180	0.0	Hand bulb sample
		10	18.0	5.8	200	6.9	Hand bulb sample
		15	20.0	1.8	1000	27.5	Hand bulb sample
04/24/2002	Soil Gas Point #13	5	15.0	7.5	72	2.6	Hand bulb sample
		10	16.0	5.5	2000	5600	Hand bulb sample
		15	19.0	2.0	1100	1136	Hand bulb sample
04/24/2002	Soil Gas Point #14	5	19.0	2.0	18	13.4	Hand bulb sample
		10	19.5	4.5	320	126	Hand bulb sample
		15	20.0	1.3	710	1792	Hand bulb sample
04/26/2002	MW-32	13.75-23.75	17.0	5.0	43	509.0	Vacuum pump sample
04/26/2002	MW-37	7.75-23.7	1.5	>25	7500	NA	Vacuum pump sample - 3 min purge
		7.75-23.7	2.0	>25	9500	NA	Vacuum pump sample - 5 min purge
		7.75-23.7	3.0	>25	>10,000	NA	Vacuum pump sample - 8 min purge
		7.75-23.7	4.0	>25	>10,000	NA	Vacuum pump sample - 11 min purge
		7.75-23.7	NA - Vacuum on well @ 13 min				Vacuum pump sample - 13 min purge
04/26/2002	MW-31	9.9-19.9	19.0	4.5	NA	20.6	Vacuum pump sample - 2 min purge
		9.9-19.9	18.0	7.0	NA	17.3	Vacuum pump sample - 4 min purge
		9.9-19.9	17.8	7.0	NA	15.3	Vacuum pump sample - 6 min purge
		9.9-19.9	17.6	7.0	NA	53.5	Vacuum pump sample - 8 min purge
		9.9-19.9	NA - Vacuum on well @ 10 min				Vacuum pump sample - 10 min purge
04/26/2002	MW-04a	Not available	9.5	14.0	28	NA	Vacuum pump sample - 2 min purge
		Not available	10.0	12.5	14	NA	Vacuum pump sample - 4 min purge
		Not available	10.0	10.0	NR	NA	Vacuum pump sample - 6 min purge
		Not available	NA - Vacuum on well @ 6.5 min				Vacuum pump sample - 6.5 min purge
04/26/2002	VW-01	8-14	19.9	1.2	NA	790	Vacuum pump sample - 2 min purge
		8-14	18.5	1.5	NA	1190	Vacuum pump sample - 4 min purge
		8-14	18.5	1.5	NA	1512	Vacuum pump sample - 6 min purge
		8-14	18.7	1.2	NA	1595	Vacuum pump sample - 8 min purge
		8-14	18.5	1.5	NA	1820	Vacuum pump sample - 10 min purge
		8-14	18.5	1.1	NA	2496	Vacuum pump sample - 14 min purge

NA = not applicable; NR = no recovery.

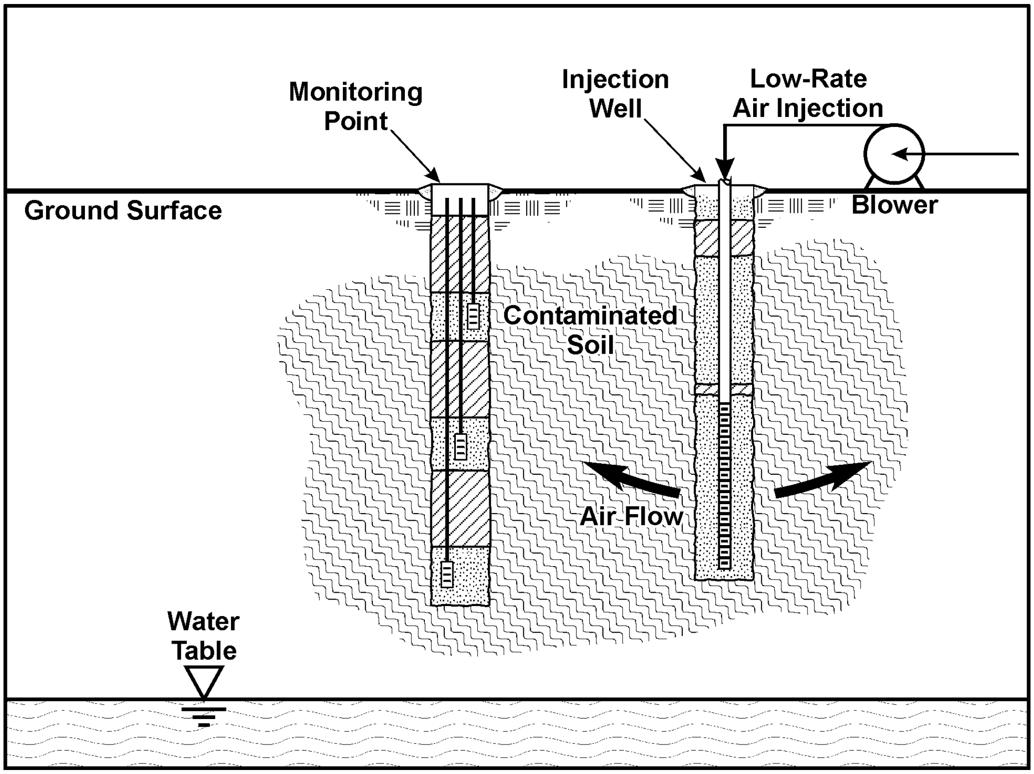

Figure 1. Active Bioventing System Schematic

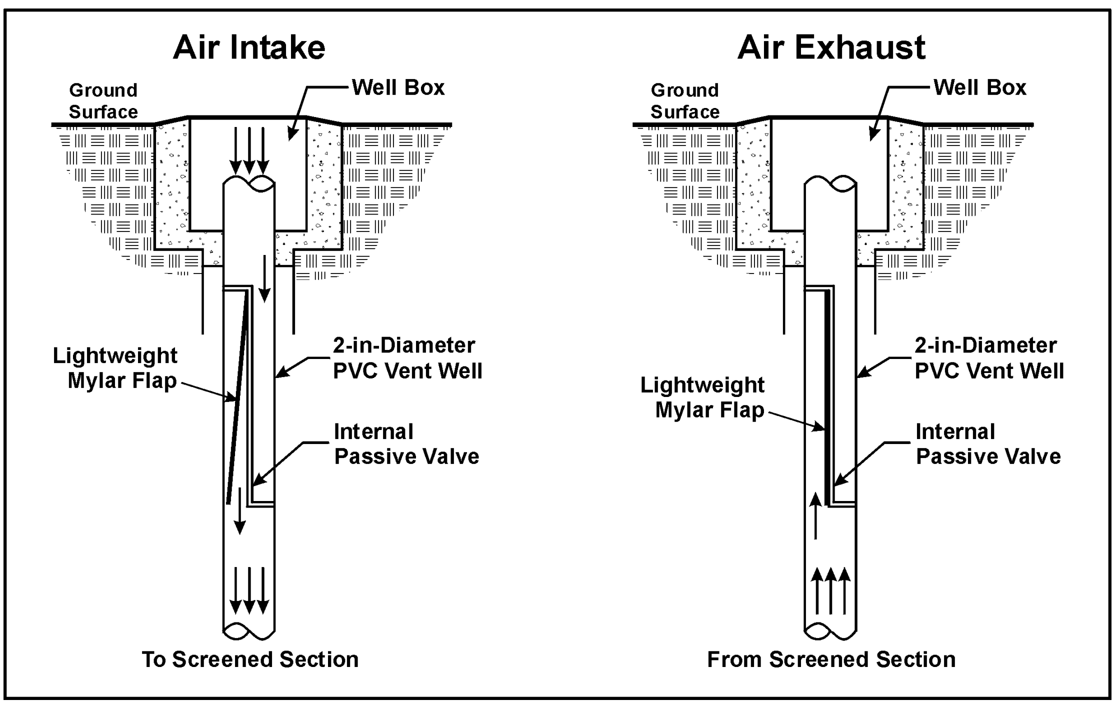

Figure 2. Passive Bioventing Valve Installation and Operation

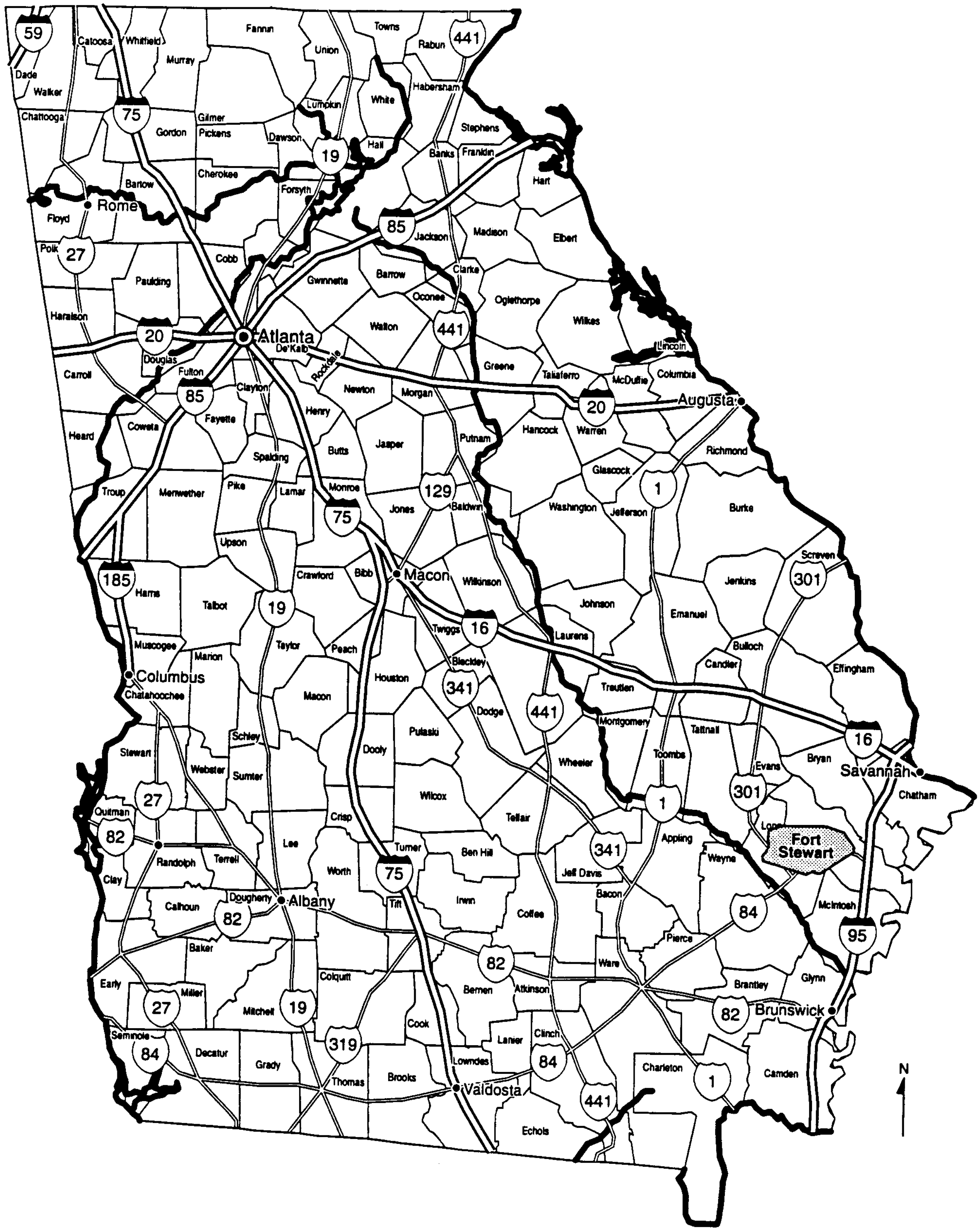

Figure 3. Regional Location Map for Fort Stewart Military Reservation, Georgia (SAIC, 2000)

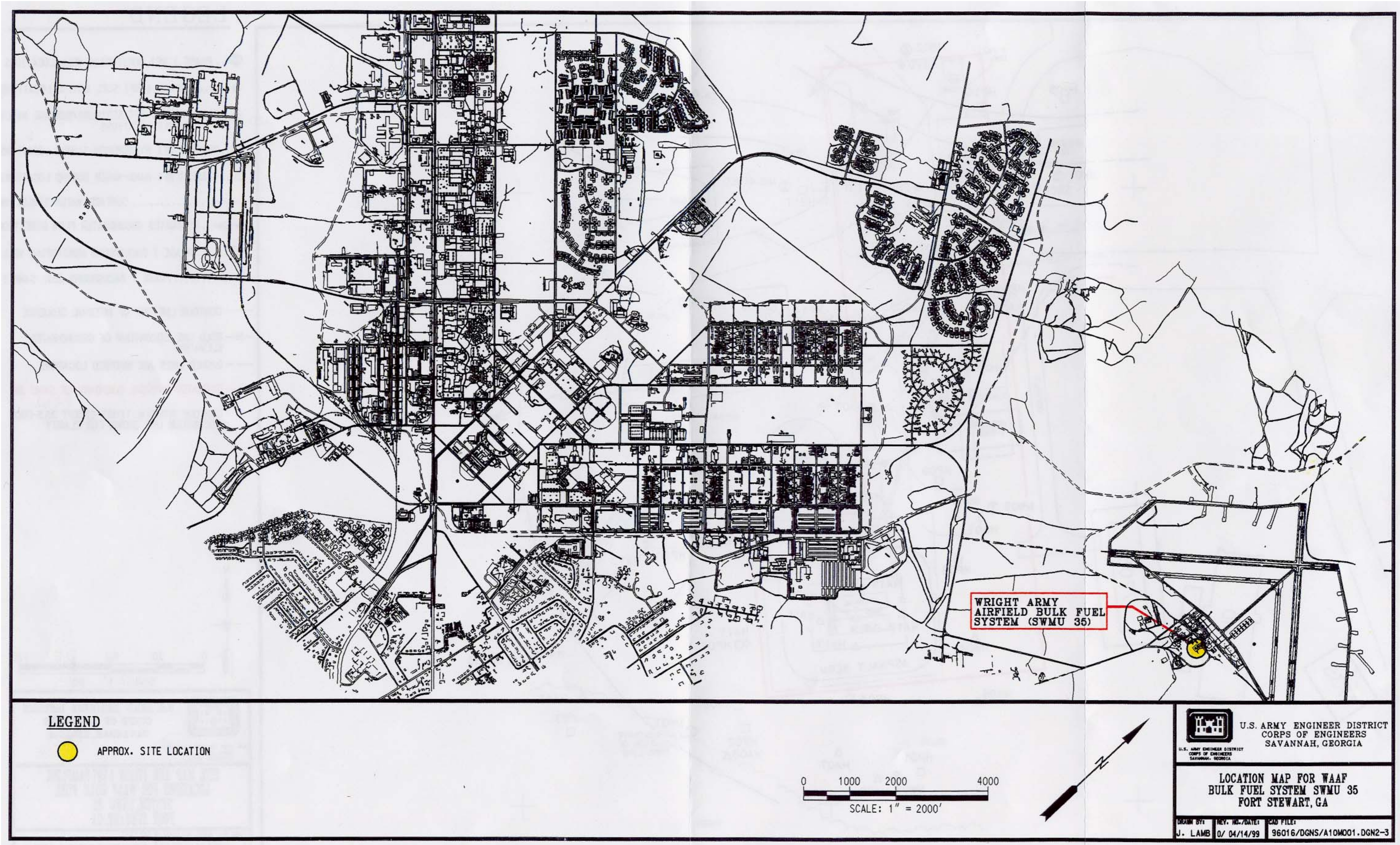

Figure 4. Location Map for Wright Army Airfield Bulk Fuel System (SWMU 35), Fort Stewart (SAIC, 2000)

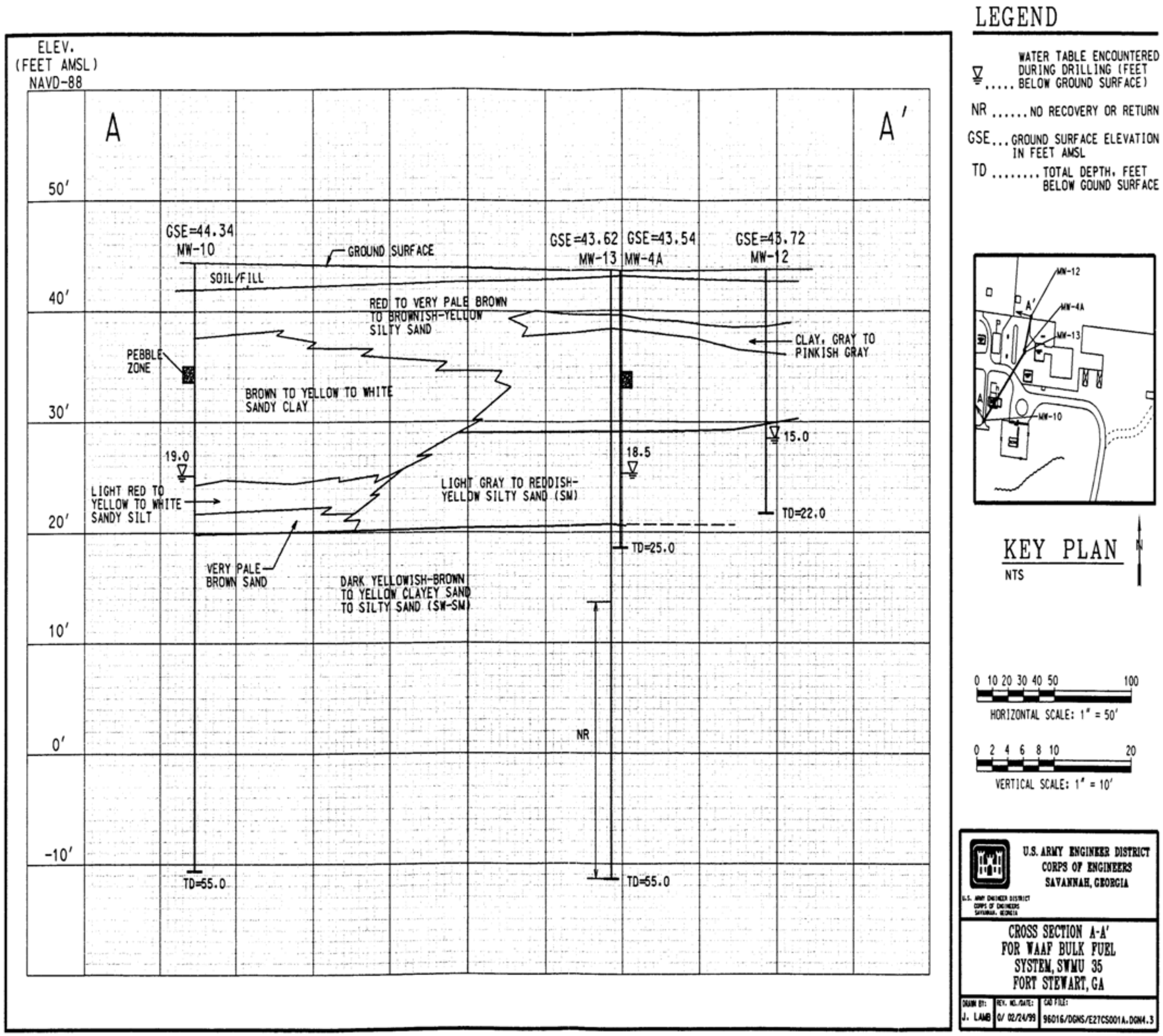

Figure 5. Geologic Cross Section A-A′ SWMU 35, Fort Stewart (SAIC, 2000)

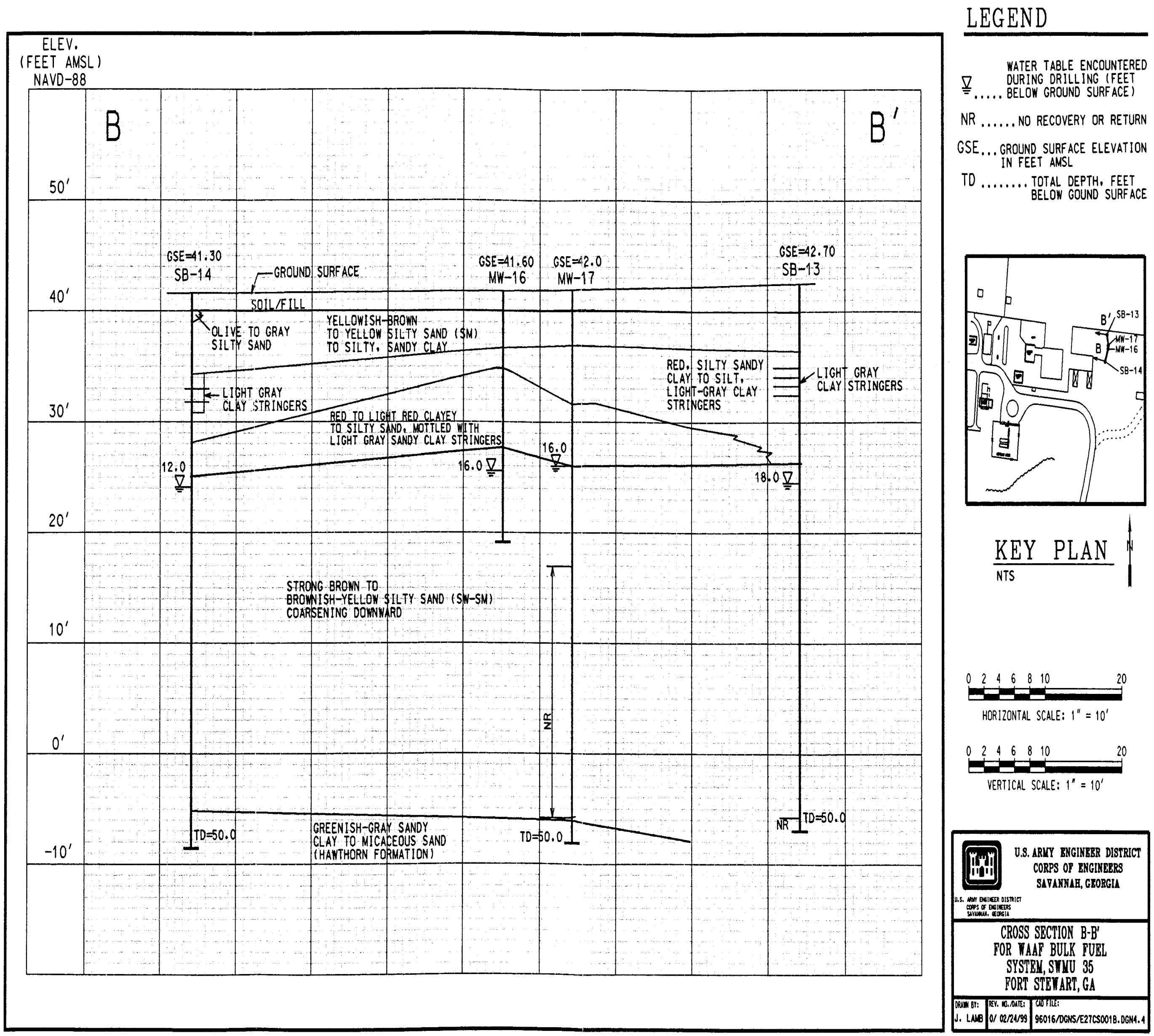

Figure 6. Geologic Cross Section B-B′, SWMU 35, Fort Stewart (SAIC, 2000)

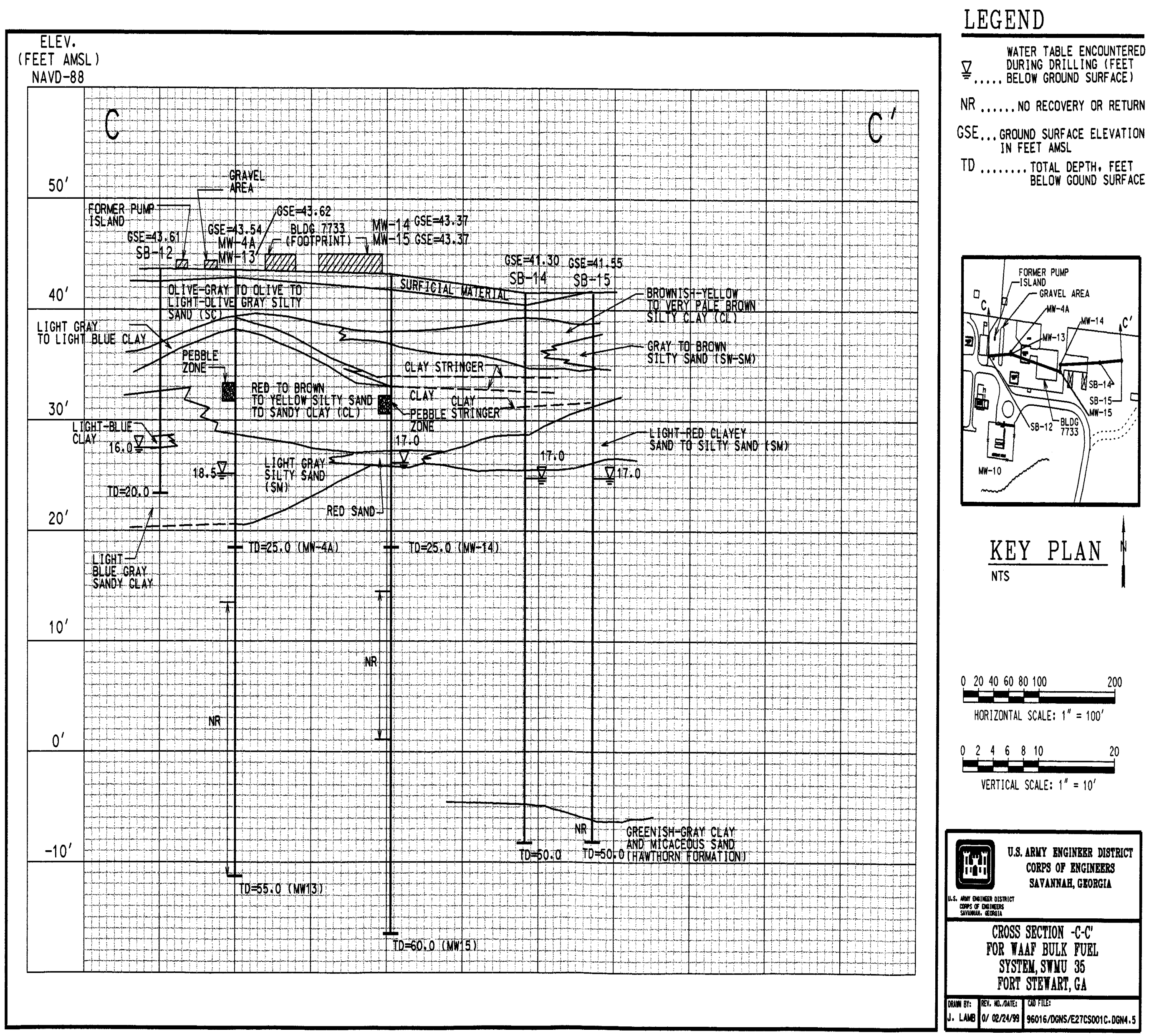

Figure 7. Geologic Cross Section C-C′, SWMU 35, Fort Stewart (SAIC, 2000)

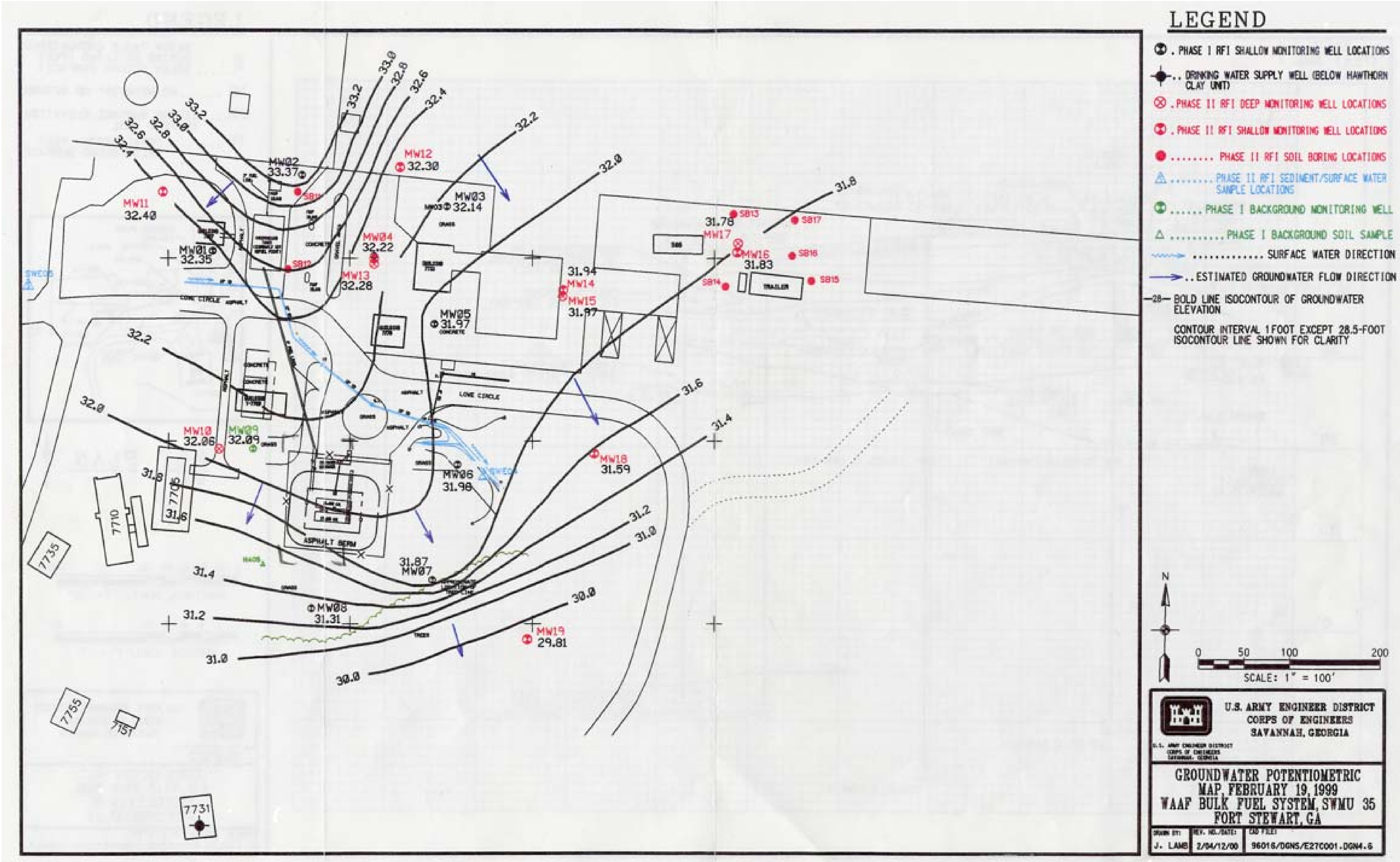

Figure 8. Groundwater Potentiometric Map (February 19, 1999), SWMU 35, Fort Stewart (SAIC, 2000)

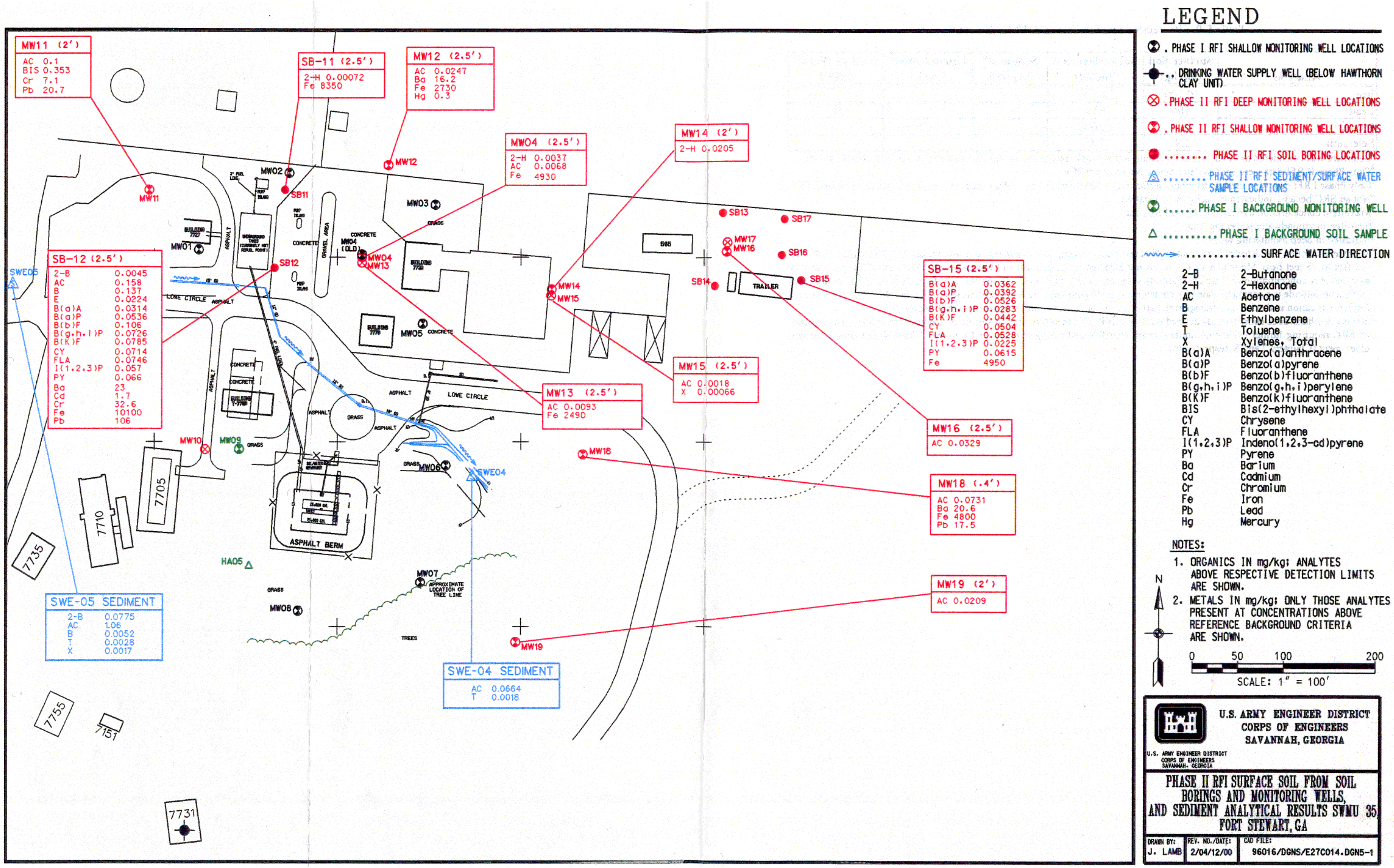

Figure 9. Phase II RFI Surface Soil from Soil Borings and Monitoring Wells and Sediment Analytical Results, SWMU 35, Fort Stewart (SAIC, 2000)

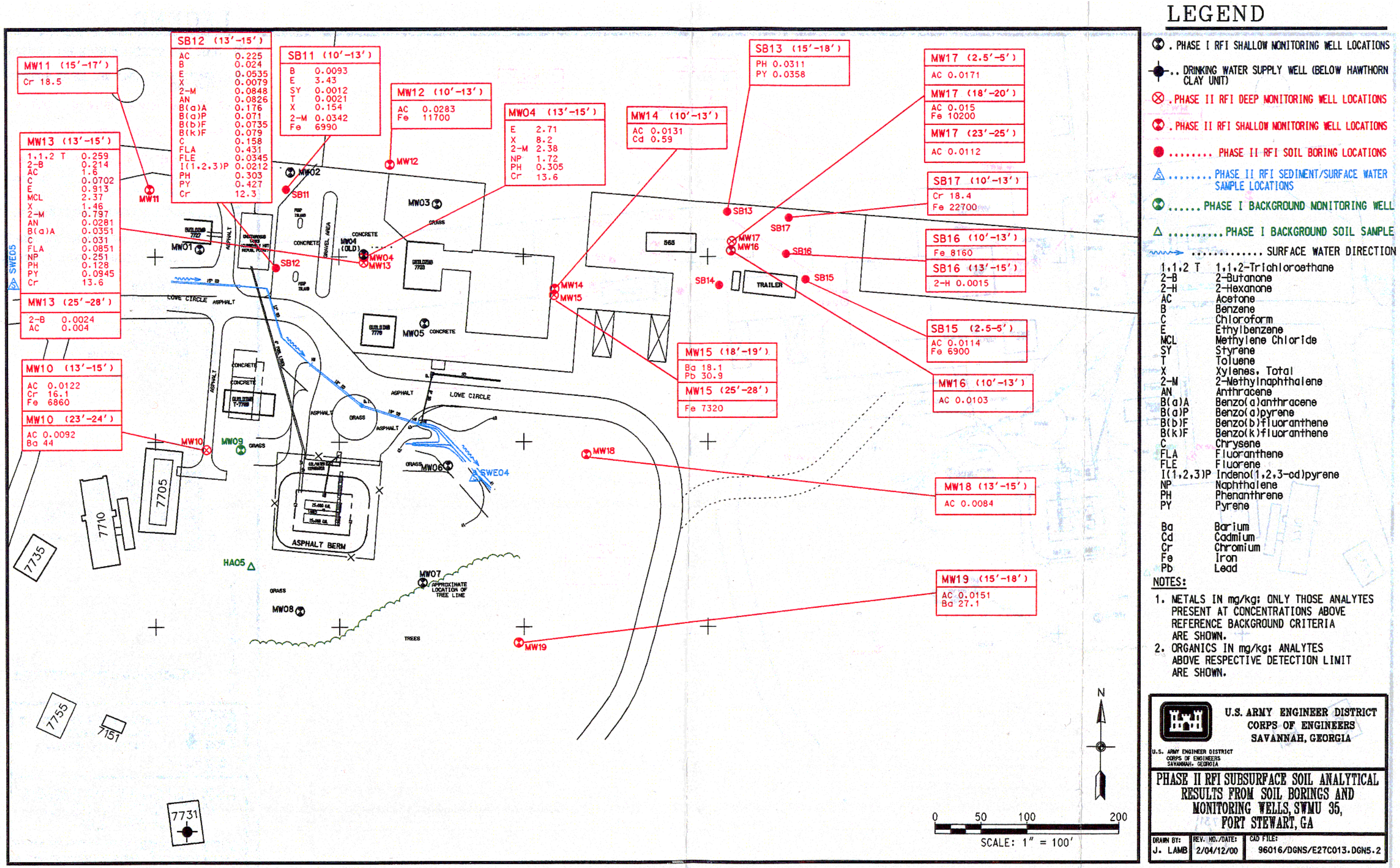

Figure 10. Phase II RFI Subsurface Soil Analytical Results from Soil Borings and Monitoring Wells, SWMU 35, Fort Stewart (SAIC, 2000)

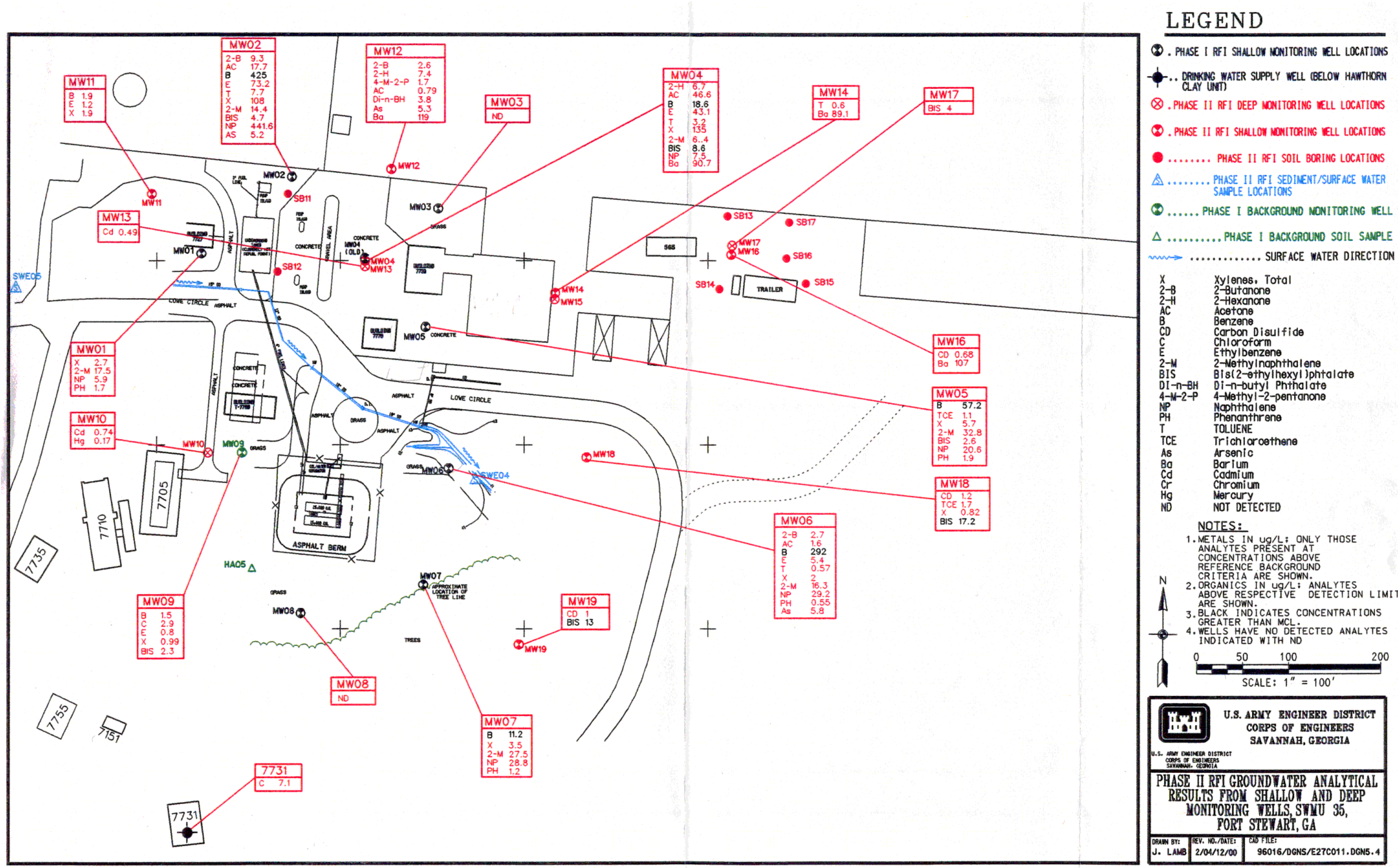

Figure 11. Phase II RFI Groundwater Analytical Results from Shallow and Deep Monitoring Wells, SWMU 35, Fort Stewart (SAIC, 2000)

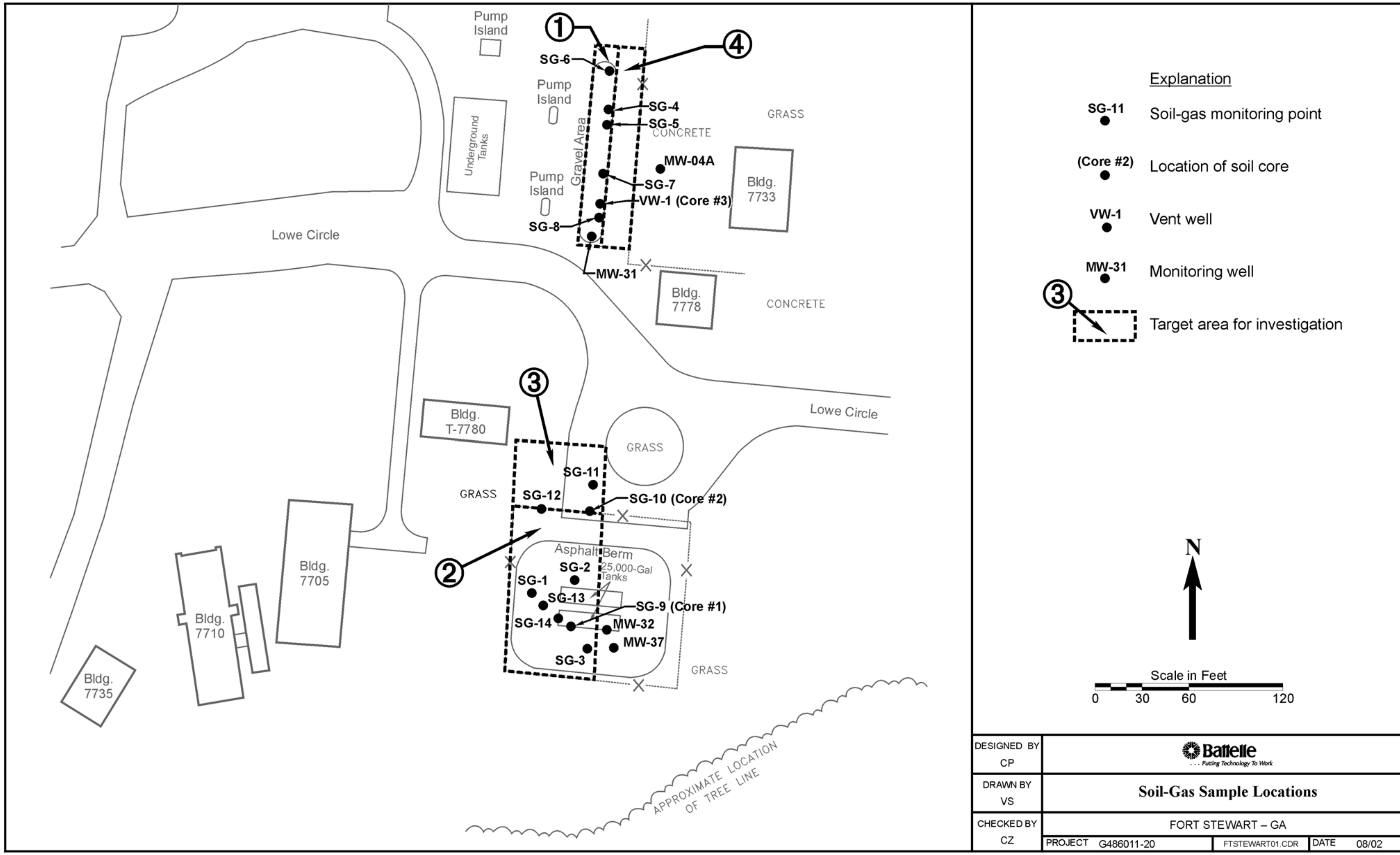

Figure 12. Soil Gas Sampling Locations at SWMU 35, Fort Stewart

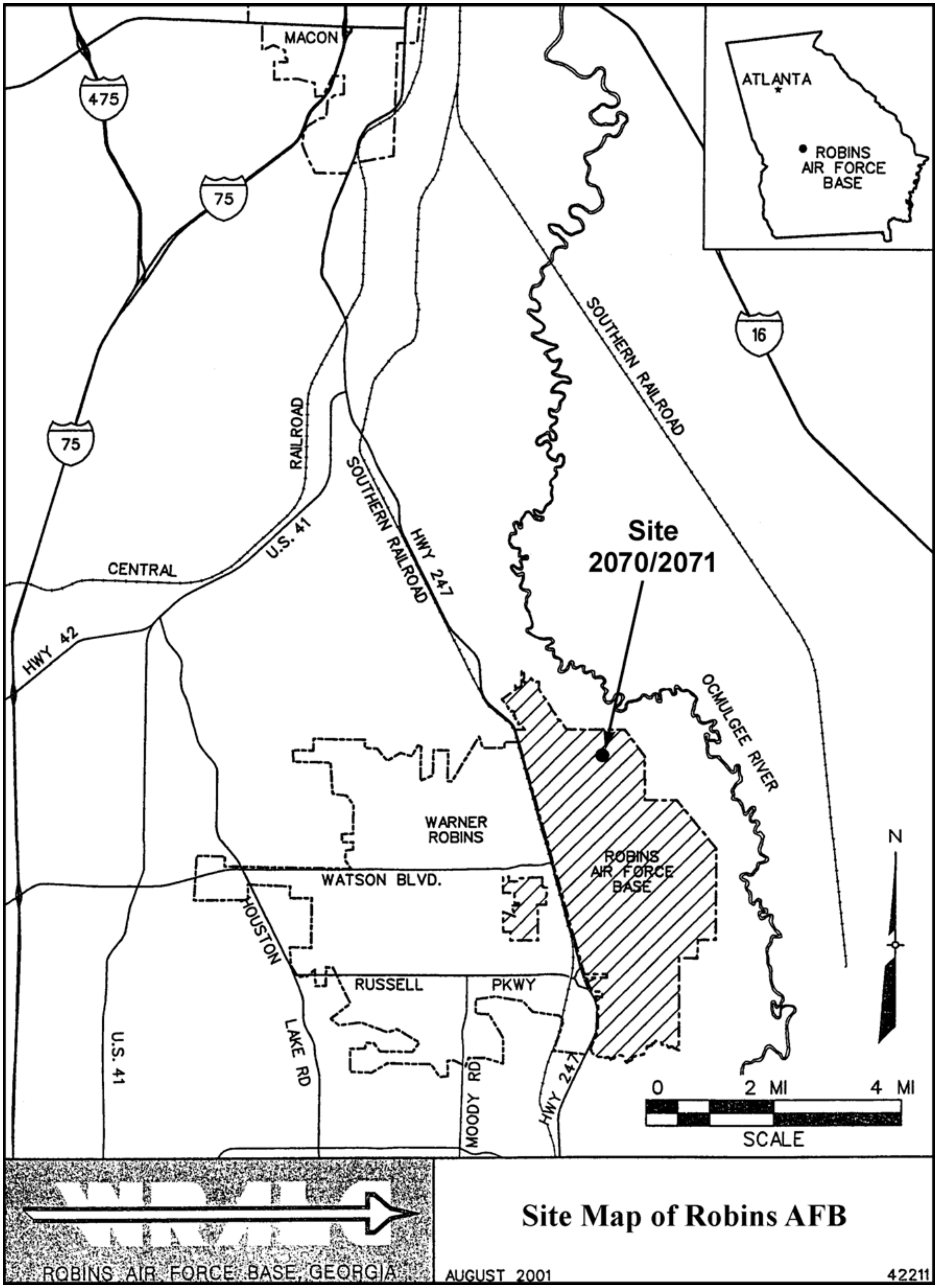

Figure 13. Site Map of Robins AFB (Earth Tech, 2001)

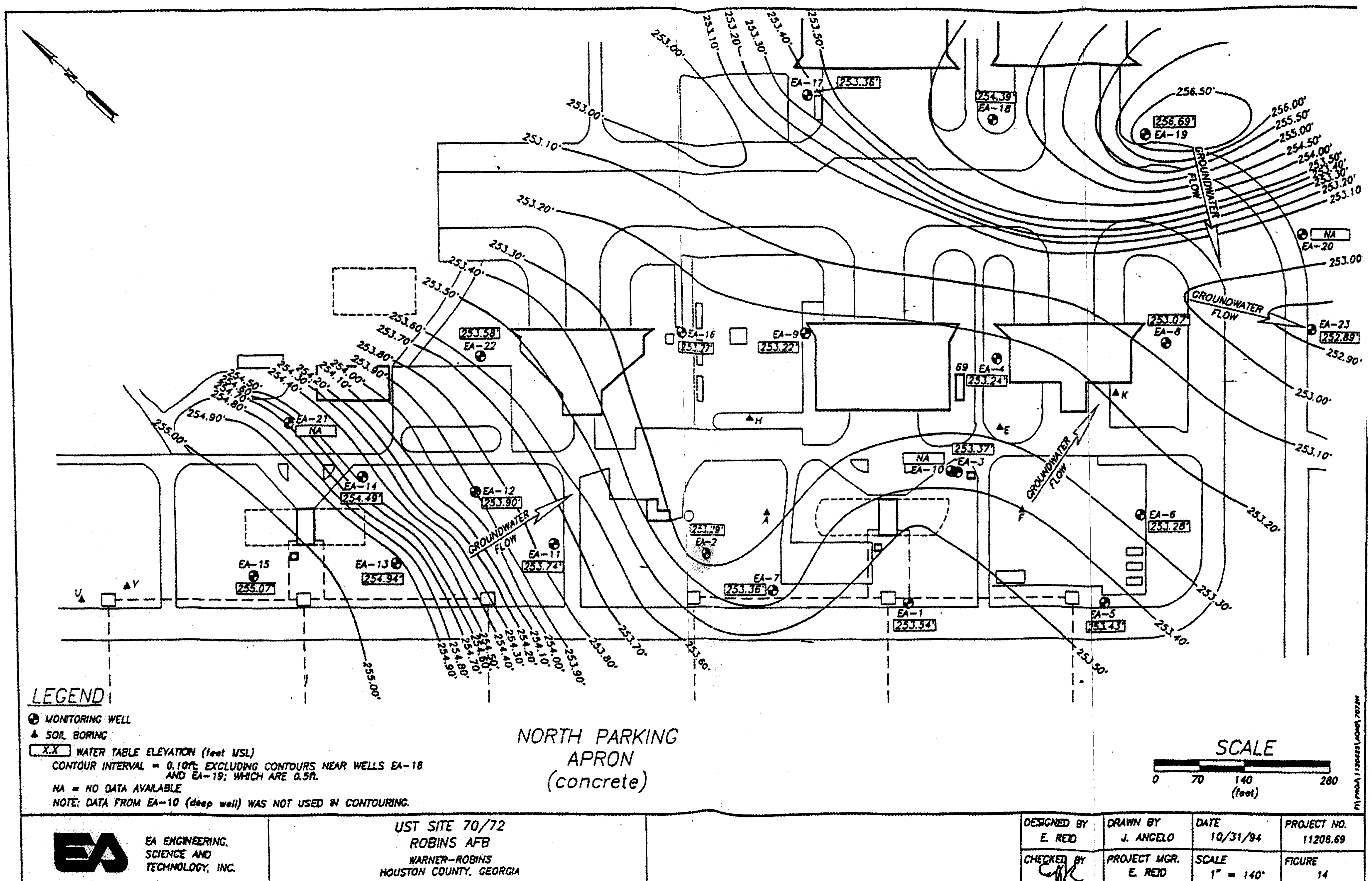

Figure 14. Groundwater Flow at Site 2070/2072, Robins AFB (Geophex, 1999)

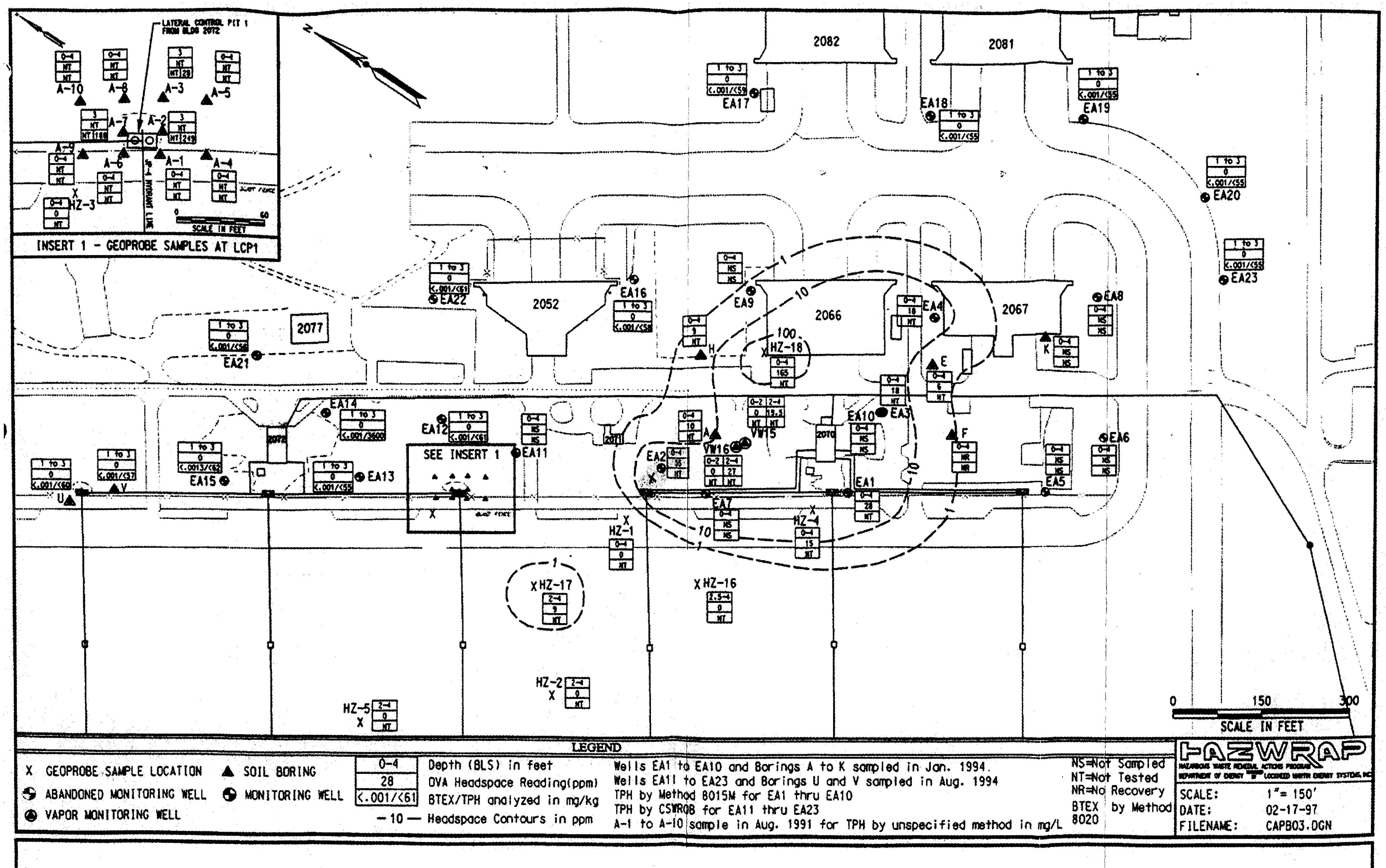

Figure 15. Surface and Subsurface Contamination Profiles (0 to 4 ft bgs) at Site 2070/2072, Robins AFB (Geophex, 1999)

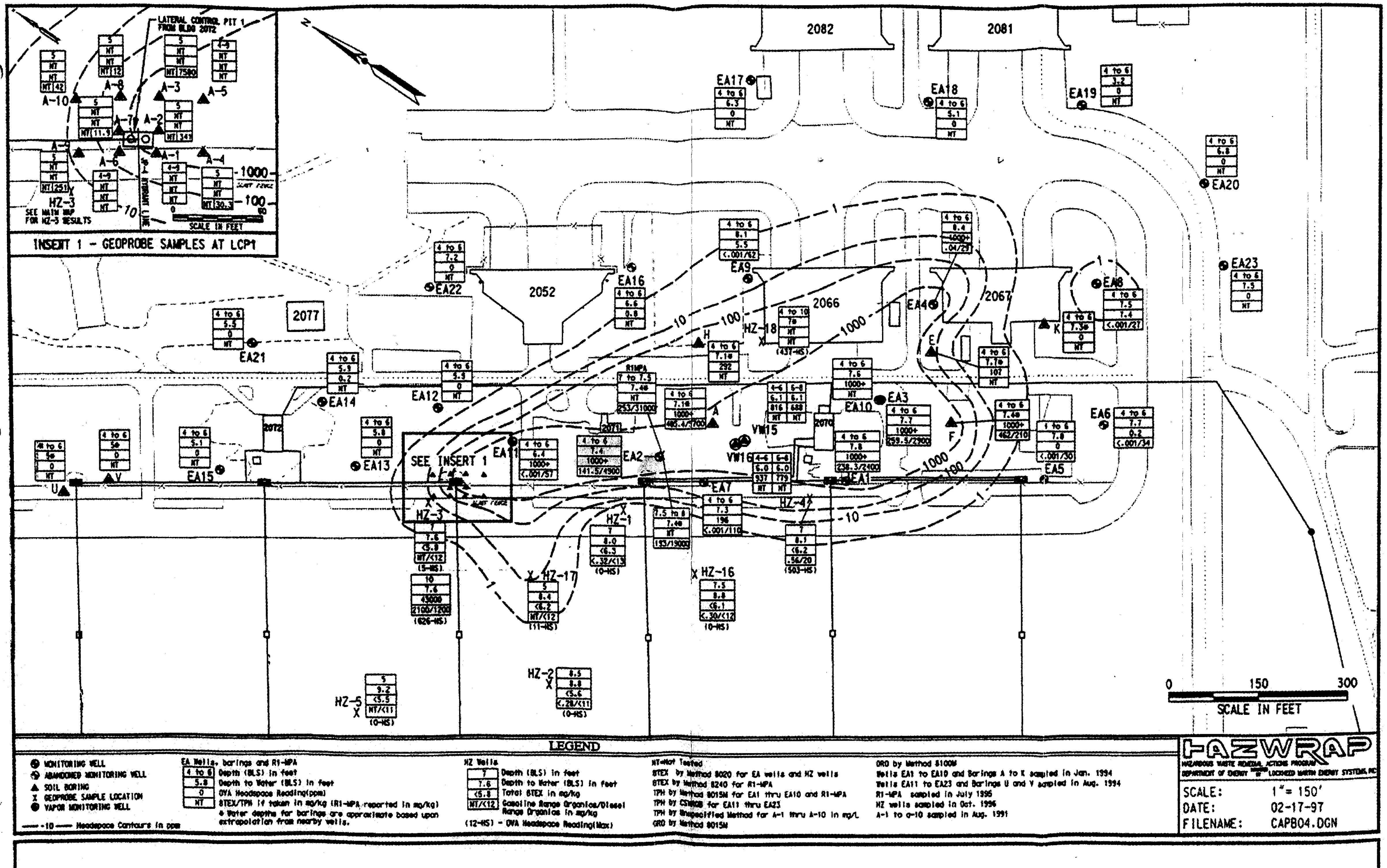

Figure 16. Subsurface Contamination (4 to 9 ft bgs) at Site 2070/2072, Robins AFB (Geophex, 1999)

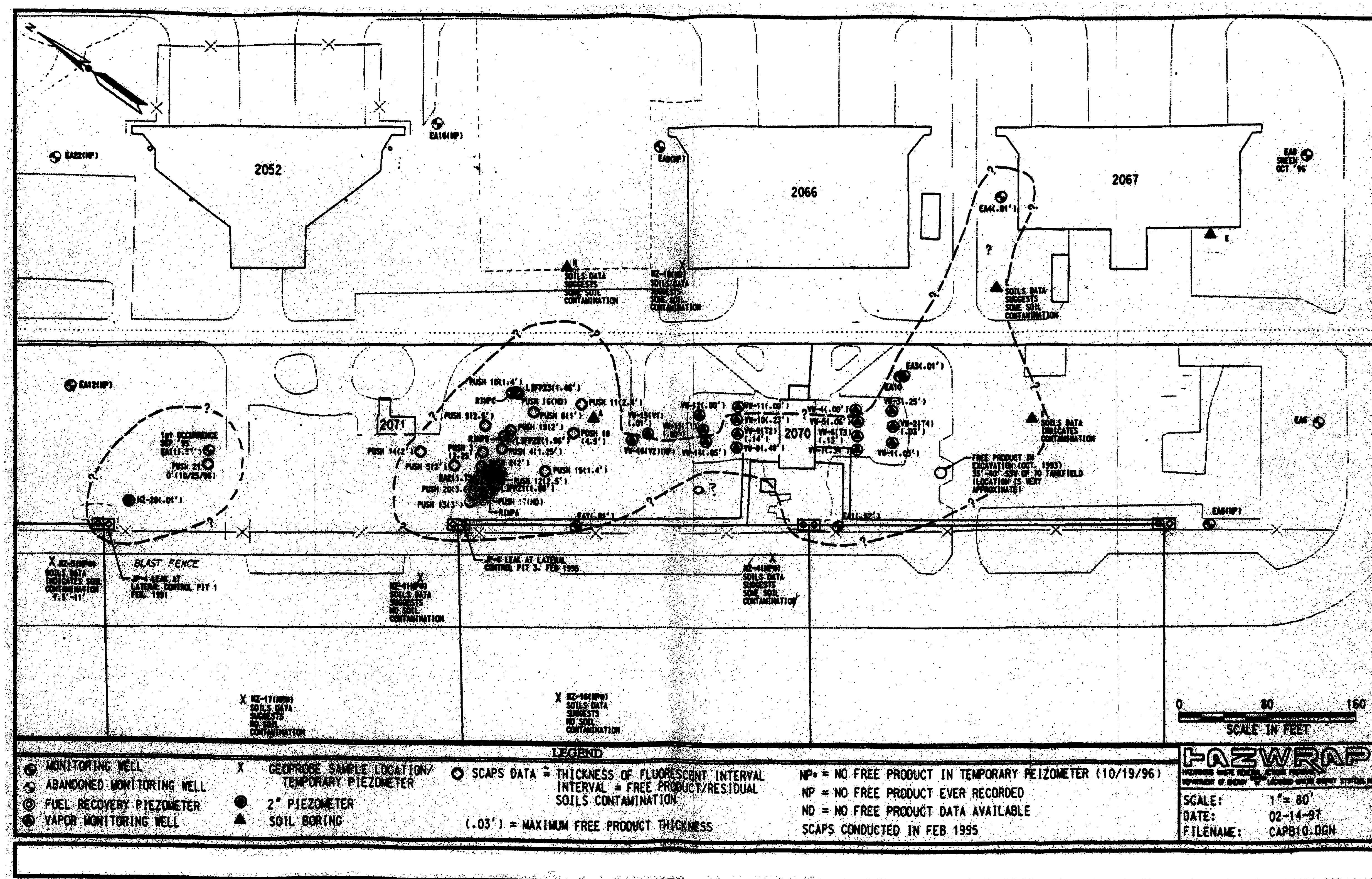

Figure 17. Free Product Thickness at Site 2070/2072, Robins AFB (Geophex, 1999)

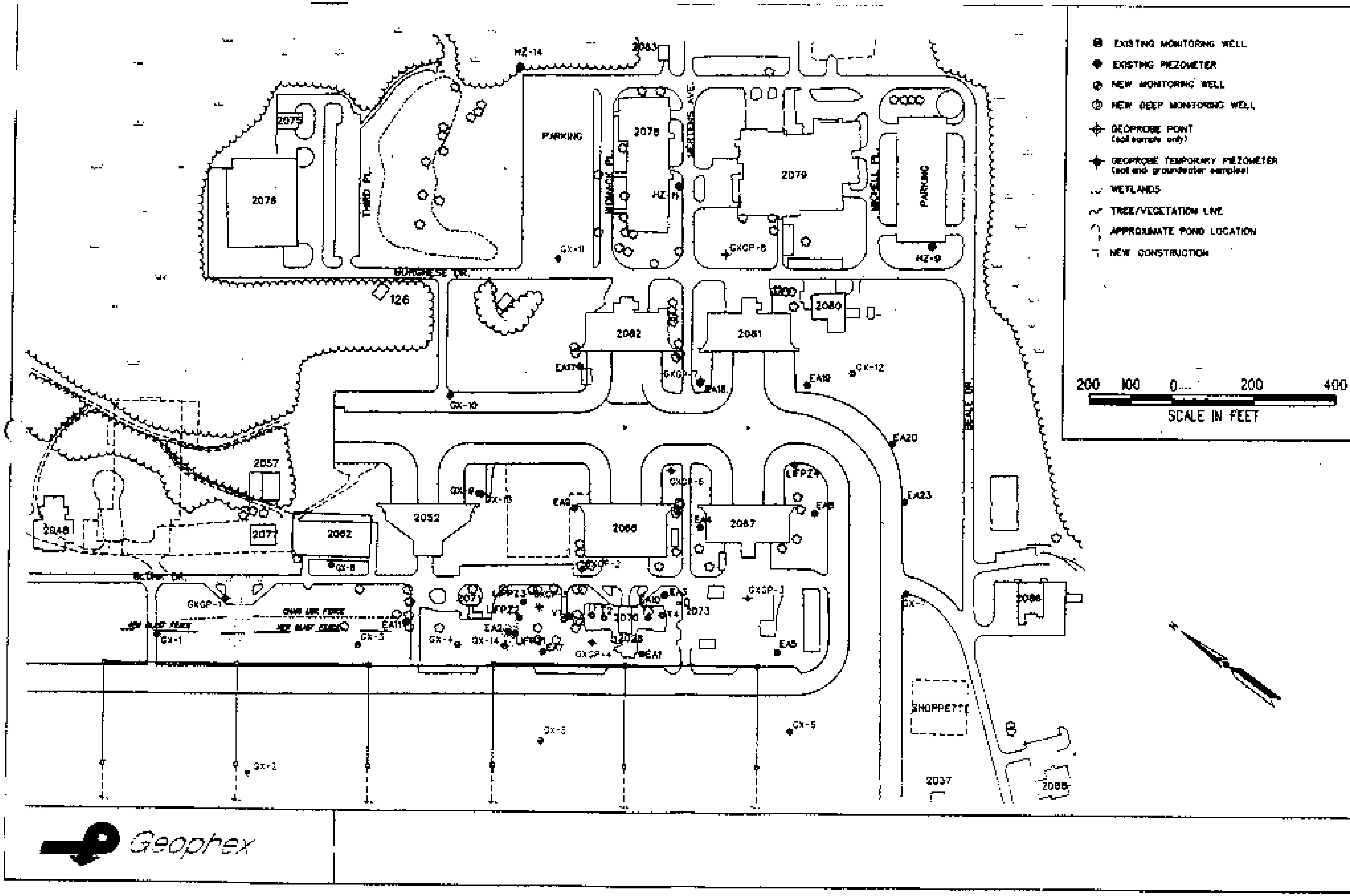

Figure 18. Vent Well Installation Schematic at Site 2070/2072, Robins AFB (Geophex, 1999)

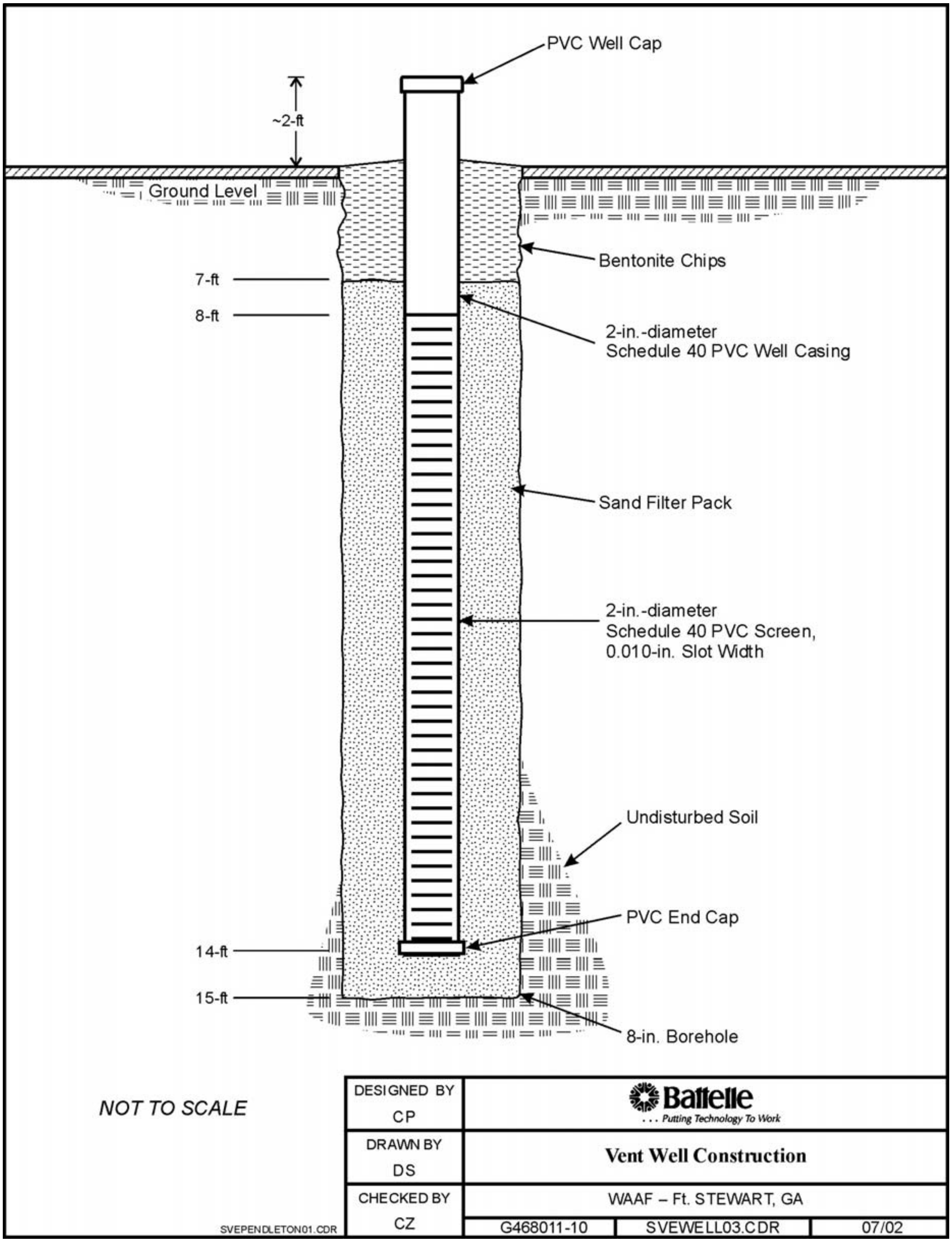

Figure 19. Vent Well Installation Schematic at Fort Stewart

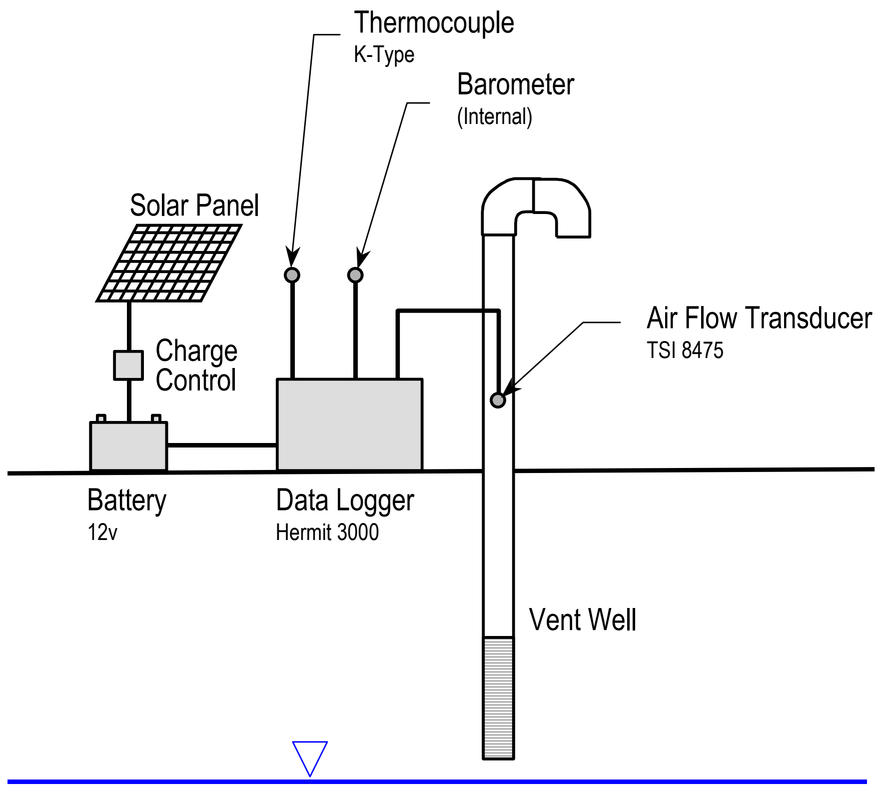

Figure 20. Monitoring System Configuration at Fort Stewart

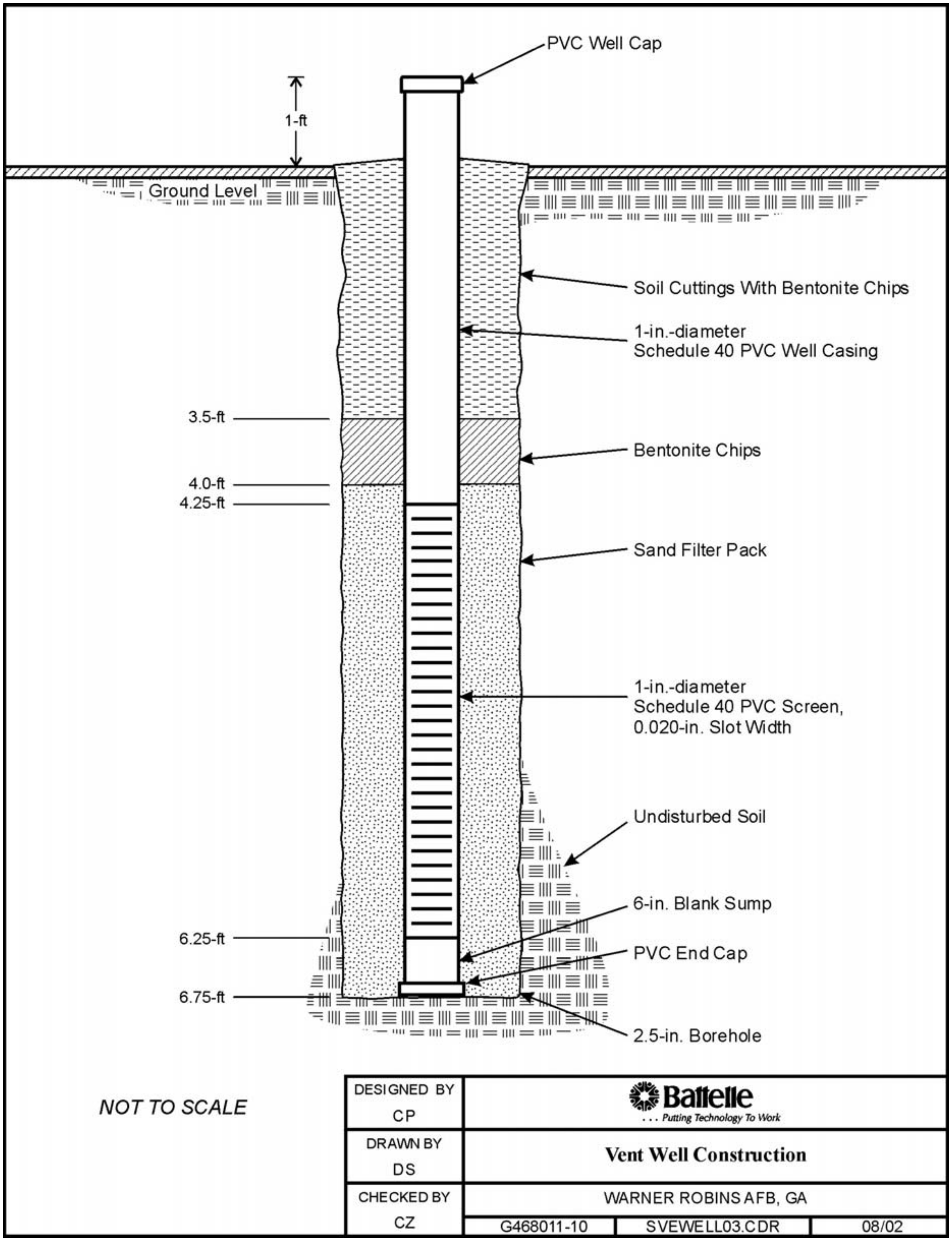

Figure 21. Vent Well Installation Schematic at Robins AFB

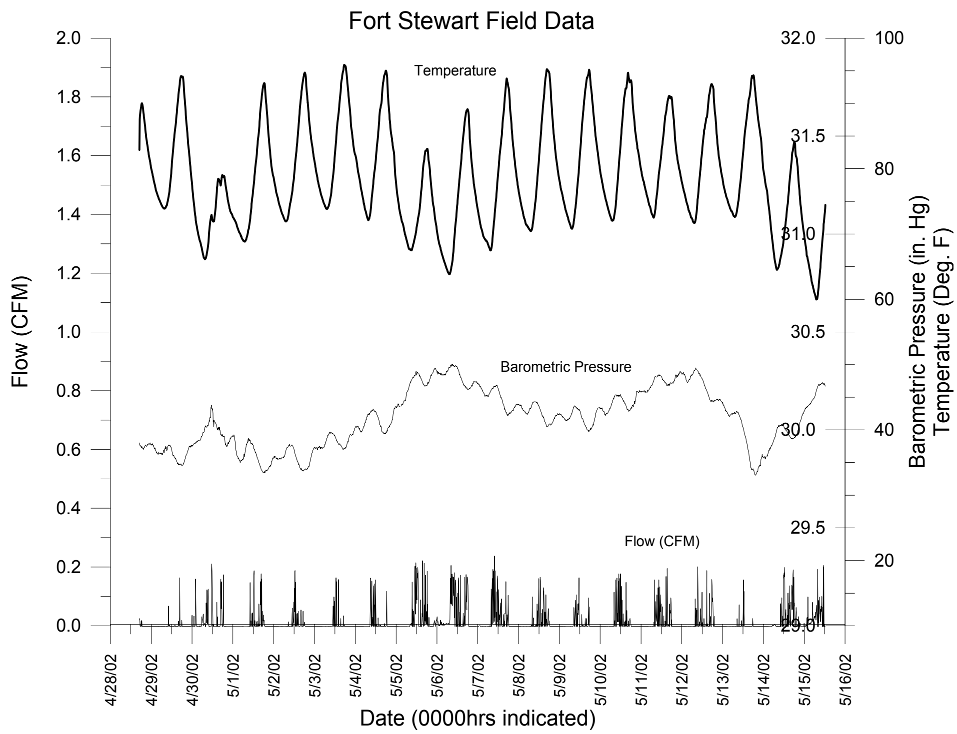

Figure 22. Fort Stewart Field Data Plot

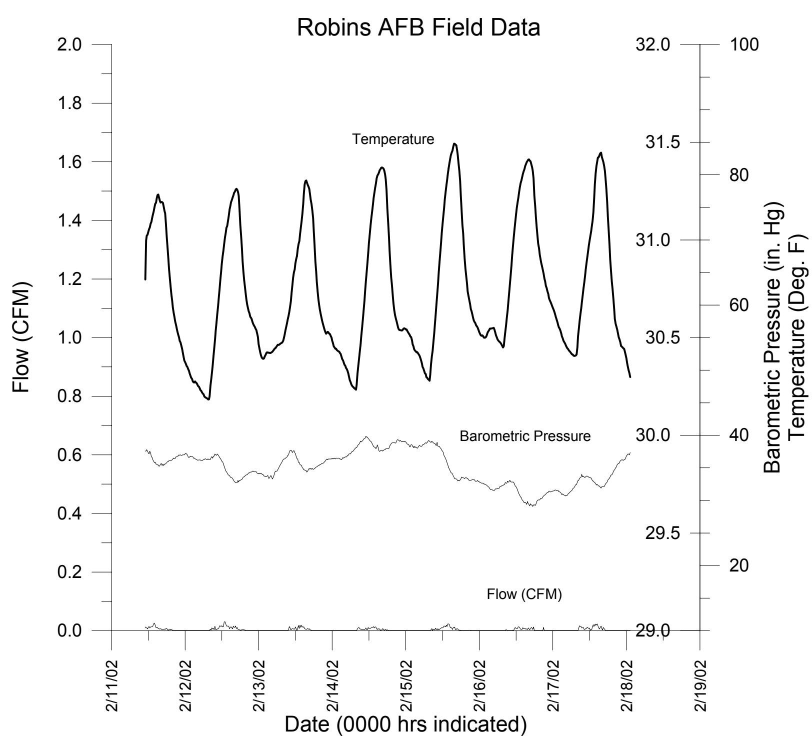

Figure 23. Robins AFB Field Data Plot